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ELECTRIC GENERATOR DEVELOPMENT FOR THE 1980'S

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This report outlines the development of a 400 HZ, 30 KW generator, to be used in a Mobile Electric Power Plant (MEPP). The developed generator complies with the new standard for ground power, MIL-STD-704C. A computer aided design was used to develop engineering generator system parameters from desired specified output requirements. The computer program was fully substantiated by actual test results.

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SUMMARY

A. GENERAL. Because the military standard for mobile electric power generation requires a substantial improvement in the quality of the power being produced, new equipment utilizing the latest electronic system control technology will be required to meet the high level of stability set forth in the new specification.

B. PROCEDURES AND RESULTS. In the current exploratory development program, an existing 30 kilowatt diesel driven generator set with a high reliability was utilized. To make any necessary design changes, a computer program was developed to calculate the generator's electrical parameters from the physical characteristics.

The current exploratory development program has been organized into three basic groups. The first of these specifies the major requirements as stated in MIL-STD-704C. These individual requirements are indicated in Figures 1 through 4. The second group of the program presents the calculated results of the computer program developed to fulfill the individual requirements of the first group. These calculated results are shown in Figures 5 through 10 and Tables 1 through 3, Summary of Design Calculations. The third group provides verification of calculated results by actual test data. The critical part of this test data is recorded in Figures 11 and 12. Complete verification of the program calculations are presented in Appendices A through E.

1. The procedure adopted analyzed the performance of the generator under various loading conditions to determine if the unit was capable of generating power for aircraft utilization equipment in conformance with MIL-STD-704C. The analysis indicated that some of the machine parameters required further investigations. Calculations to make the proper changes were made and modifications suggested.

2. Many of the requirements of MIL-STD-704C were related to the control system of the MEPP. Several computer programs were developed to design new voltage and frequency control circuits. Figures 8 through 10 represent the output of those computer programs. The new controlling circuits that are to be used on the generator may be in the form of a microcomputer. A concurrent development program is being done to design this system. When both programs are completed, they will be combined with each other to become a new MEPP power system.

3. To confirm computer calculations and obtain the proper design parameters, a comprehensive test program was developed and implemented. All the requirements of MIL-STD-704C regarding ground support gear were investigated and documented according to the MIL Standard test directive (MIL-STD-705B). This directive describes the proper method of testing a generator's performance characteristic to any military specification.

4. When the obtained test data was compared to results calculated by the computer, it was observed that calculated and obtained test results were in agreement. Table 4 presents the requirements of various standards and specifications as compared to actual test results.

5. After completing several design changes and retesting the generator output, a generator design that conforms to MIL-STD-704C was attained.

6. At present a generator that conforms to the requirements of MIL-STD-704C is being modified to adapt to a microcomputer control system.

C. CONCLUSIONS AND RECOMMENDATIONS. A new standard of power is now required for ground support equipment as described in MIL-STD-704C. A study was made to obtain an engine generator that was most likely to comply with the new requirement. A DOD 30 KW diesel driven generator was obtained due to its favorable electro-mechanical characteristics and availability. A computer program was developed to calculate generator electrical characteristics from generator mechanical parameters. To verify computer results, a generator test program was developed and employed. Results indicated that the computer program and generator test data, in most cases, were in agreement.

From this data design changes were incorporated on the generator. The result is a generator that complies with MIL-STD-704C.

It is recommended that the generator with the modified design be used in any new or retrofitted mobile electric power plant that is to be put into the fleet.

In the future, it is recommended that the design criteria used to develop a 30 KW engine-generator power system be used for all design projects of the same type.

PREFACE

Almost all the aircraft electrical power ground support equipment used by the Navy was designed over a decade ago and has not kept pace with the rapidly advancing technology. Due to the existing grade of power (per MIL-STD-704A), equipment problems have been encountered. There has been an effort to revise the existing specification which resulted in the preparation and issue of MIL-STD-704C, "Aircraft Electrical System Characteristics".

The present ground support equipment does not meet the new specifications of MIL-STD-704C. Because of this, a development program has started to replace the existing Mobile Electric Power Plants (MEPPs). The new MEPPs will provide aircraft systems with necessary power requirements in conformance with the new specification during periods of ground maintenance and pre-flight checks.

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I. INTRODUCTION

A. Current and proposed Navy aircraft carry an appreciable quantity of electrical and electronic equipment that must perform satisfactorily if mission goals are to be achieved.

B. In order to perform properly, this equipment must be supplied a required quality of input power. For instance, AC devices must be supplied with voltage within certain amplitude and frequency limits and the voltage wave form can contain only a very limited amount of distortion. Similarly, DC devices can only tolerate a small amount of ripple at their required voltage levels. The requirement for proper voltage regulation and minimal frequency fluctuation is essential for the proper operation of the equipment during both steady state and transient operating conditions. To avoid the possibility of equipment malfunction due to poor electrical power quality, the characteristics of electrical power supplied to utilization equipment aboard aircraft are delineated by specification.

C. From approximately 1959 through 1975 the specification used was MIL-STD-704A, "Electric Power, Aircraft, Characteristics and Utilization Of". However, equipment problems recently encountered could be traced directly to the power generation equipment supplying it with electricity, even though those generators complied with MIL-STD-704A. An effort to revise the specification resulted in the preparation and issuance of MIL-STD-704B, "Aircraft Electrical System Characteristics" in November 1975, which was superseded by MIL-STD-704C in December 1977.

D. Because of the more stringent requirements of MIL-STD-704C, the Ground Support Equipment community recognized the need to develop Mobile Electric Power Plants (MEPPs) that would provide aircraft systems the necessary power requirements in conformance with the new specification during periods of ground maintenance and pre-flight checks. The development of these MEPPs is most essential because it is highly unlikely that the smaller, lighter weight aircraft of the future will have auxiliary onboard power units to operate their power hungry avionic systems when the airplane's propulsion engine is not running. The heart of the MEPP is the engine-generator section which must provide power during all phases of ground maintenance. This program deals with the development of a 30 KW generator to be used in future Mobile Electric Power Plants.

E. This report supersedes report NAEC-GSED-107.

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II. EQUIPMENT AND PROCEDURES

A. In the current program, an existing, highly reliable diesel driven generator set is being utilized as the basic building block. By specification, this generator set has a required MTBF of 500 hours. It was chosen because it is one of the most advanced 400 Hertz generators and provides the most promise of complying with the requirements of MIL-STD-704C.

B. After considering the many alternatives, a decision was made to have the personnel at the Naval Air Engineering Center design the new power system. This decision was not only cost effective, but also provided an opportunity to gain the much needed knowledge that would be beneficial in future projects. To help with the design stages, the services of a consultant was obtained who is an expert in the field of power generation and has worked with industry on projects which are related to the present program and has an outstanding knowledge of practical applications.

C. Along with hiring a consultant, a computer program was obtained and developed to make generator design calculations. This program is helpful in that from the physical dimensions of the generator, many of the electrical parameters can be calculated. Output data such as line current, field current, field voltage, flux densities, and various losses can be obtained for several power factors. The program was run and the input data, design sheet data, and the computer results were all tabulated.

D. To verify the validity of the results of the computer program, a generator test program was developed. The engine and generator were modified for laboratory experimentation and upon completion, the test program employed. A detailed description of the various test methods and test results can be seen in the appendix section of this report.

III. ANALYSIS

A. Suggested modifications to the existing engine generator set were determined by two methods. The first method was the computer program that was developed to provide theoretical electrical output characteristics based on the generator's physical parameters. The second source of information came from the generator test program results. Using the results of both programs various modifications were incorporated on the generator to have it conform to MIL-STD-704C.

B. Appendix E contains the formulas used to calculate the generator's performance at various loading conditions. The results of the computer program are indicated in Tables 1, 2 and 3 in the following pages. Various generator parameters are indicated at load points of 0, 50, 100, 150 and 200 percent load in Table 1.

C. The following pages indicate calculated values of generator performance under various load conditions. Output values were based on calculated electrical parameters that were obtained from the physical characteristics taken from generator design generator sheets.

D. The 30 KW generator was obtained on a test bed with a 90 horsepower Hercules/White diesel engine used as the prime mover. The engine and generator were modified for laboratory instrumentation and tested. Each portion of MIL-STD-704C was tested according to the Test Method prescribed in MIL-STD-705B. Using the test method described in MIL-STD-705B, the generator was first tested in accordance with MIL-STD-704B and then to the most recent MIL Standard, 704C. When a clarification of a requirement was needed, the generator was tested to MIL-G-21480 which is an aircraft generator specification. A comparison of the requirements of MIL-STD-704B versus MIL-STD-704C versus MIL-G-21480 and the results of the generator test can be observed on Table 4.

TABLE 1. SUMMARY OF DESIGN CALCULATIONS
(OUTPUT - PERCENT LOAD) *

PERCENT LOAD		0	50	100	150	200
ϕ_ℓ	LEAK FLUX	71.00	83.17	94.2	106.3	119.0
ϕ_p	FLUX PER POLE IN KILOLINES	437.00	458.3	477.6	497.9	519.1
B_t	TOOTH DENSITY IN KILOLINES/in^2	96.5	101.1	105.4	109.8	114.5
F_p	POLE AMP TURNS	87.8	146.4	234.4	346.0	511.5
$F_{f\ell}$	TOTAL AMP TURNS	611.4	759.8	929.7	1130.1	1389.5
F_{ff}	FIELD AMPS	10.91	13.5	16.6	20.1	24.8
S	CURRENT DENSITY IN FIELD CONDUCTORS	1347.50	1674.3	2048.8	2490.40	3062.1
E_F	FIELD VOLTS	19.36	29.3	35.9	43.64	53.6
I^2R_R	ROTOR I^2R	680.3	688.8	710.0	741.90	783.7
F & W	FRICTION & WINDAGE LOSS	211.4	398.1	596.1	880.8	1331.6
W_T	STATOR TEETH LOSS	987.0	987.0	987.0	987.0	987.0
W_c	STATOR CORE LOSS	320.1	320.1	320.1	320.1	320.1
W_P	POLE FACE LOSS	528.1	541.8	583.2	652.3	749.0
W_D	DAMPER LOSS	179.3	199.5	214.7	240.2	275.8
I^2R	STATOR I^2R	0	199.9	479.6	1079.1	1918.5
	EDDY LOSS	0	0	0	0	0
	TOTAL LOSSES (W)	2906.3	3255.4	3891.0	4901.7	6365.9
	RATING (KW)	0	14.9	29.9	44.9	59.9
	RATING AND LOSSES (KW)	2.90	18.2	33.8	49.8	66.3
	PERCENT LOSSES	100.0	17.8	11.4	9.8	9.6
	PERCENT EFF	0	82.1	88.5	90.16	90.4

* Formulas for calculations in Appendix E.

TABLE 2. SUMMARY OF DESIGN CALCULATIONS
SALIENT POLE (COMPUTER INPUT)

PARAMETERS		
KVA	GENERATOR KVA	37.5
E	LINE VOLTS	208
E_{PH}	PHASE VOLTS	120
m	PHASES	3
f	FREQUENCY	400
P	POLES	24
RPM	SPEED	2000
I_{PH}	PHASE CURRENT	104
P.F.	POWER FACTOR	.8
K_c	ADJUSTMENT FACTOR	1
	OPTIONAL LOAD POINT	.5
STATOR STACK		
d	STATOR PUNCHING I.D.	13.5
D	STATOR PUNCHING O.D.	16.5
ℓ	GROSS STATOR CORE LENGTH	6.5
n_v	NUMBER OF DUCTS	0
b_v	RADIAL DUCT WIDTH	0
K_I	STACKING FACTOR (STATOR)	.95
k	WATTS/LB	13.5
B	DENSITY	77.4
STATOR SLOT		
	TYPE OF SLOT	2
b_o	SLOT OPENING	.11
b_1	SLOT WIDTH ACROSS TOP	0
b_2	INSIDE WIDTH ACROSS BOTTOM	0
b_3	OUTSIDE WIDTH ACROSS BOTTOM	0
b_s	SLOT WIDTH ACROSS BOTTOM	.23
h_o	HEIGHT OF SLOT NECK	.03
h_1	DISTANCE BETWEEN SLOT OPENINGS	.456
h_2	DISTANCE FROM UPPER OPENING TO TOP SLOT	0
h_3	DISTANCE BETWEEN SLOTS	.014
h_s	SLOT DEPTH	.65
h_t	DISTANCE FROM UPPER SLOT TO NECK	.029
h_w	DISTANCE FROM UPPER SLOT TO TAPER	.075
Q	STATOR SLOTS	108
STATOR WINDING		
	TYPE OF WINDING	1
	TYPE OF COIL	0
n_s	CONDUCTORS/SLOT	16
y	SLOTS SPANNED	3
c	PARALLEL CIRCUITS	12
	STRAND DIAMETER OR WIDTH	.051
N_{ST}	NUMBER OF STRANDS PER CONDUCTOR IN DEPTH	1
N'_{ST}	NUMBER OF STRANDS PER CONDUCTOR	1
	STATOR STRAND T'KMS	0
d_b	DIAMETER OF BENDER PIN	.5
ℓ_{e2}	COIL EXTENSION BEYOND CORE	.75

TABLE 2. SALIENT POLE (COMPUTER INPUT) (CONTINUED)

STATOR WINDING (CONTINUED)		
h_{ST}	HEIGHT OF UNINSULATED STRAND	0
h'_{ST}	DISTANCE BETWEEN CENTERLINES OF STRANDS IN DEPTH	.228
	PHASE BELT/ANGLE	60
τ_{SK}	SKEW	.393
$X_s{}^\circ C$	STATOR TEMP °C	75
ρ_s	RESISTIVITY OF STATOR WINDING	.680
GAP		
g_{min}	MINIMUM AIR GAP	.035
g_{max}	MAXIMUM AIR GAP	.035
CONSTANTS		
C_1	FUND/MAX OF FIELD FLUX	0
C_W	WINDING CONSTANT	0
C_P	POLE CONSTANT	0
L_E	END EXTENSION LENGTH	0
C_m	DEMAGNETIZING FACTOR	0
C_q	CROSS MAGNETIZING FACTOR	0
ROTOR STACK		
b_h	POLE HEAD WIDTH	1.238
b_p	POLE BODY WIDTH	.72
h_h	POLE HEAD HEIGHT	.34
h_f	POLE BODY HEIGHT	1.57
ℓ_p	POLE BODY LENGTH	6.625
ℓ_n	POLE HEAD LENGTH	6.625
αC	POLE EMBRACE	.77
d_r	ROTOR O.D.	13.43
K_1	STACKING FACTOR (ROTOR)	.95
	WEIGHT OF ROTOR IRON	259.9
X_1	POLE FACE LOSS FACTOR	1.17
DAMPER BAR		
b_{bo}	WIDTH OF SLOT OPENING	.047
h_{bo}	HEIGHT OF SLOT OPENING	.017
h_{bl}	RECTANGULAR BAR THICKNESS	0
b_{bL}	RECTANGULAR SLOT WIDTH	0
n_b	NUMBER OF DAMPER BARS	4
ℓ_b	DAMPER BAR LENGTH	6.625
τ_b	DAMPER BAR PITCH	.29
ρ_b	DAMPER BAR RESISTIVITY @ 20°C	.68
$X_D{}^\circ C$	DAMPER BAR TEMP °C	75
FIELD		
N_P	NUMBER OF FIELD TURNS	56
ℓ_{tr}	MEAN LENGTH FIELD TURN	15.726
	FIELD COND. DIAMETER OR WIDTH	.1016
	FIELD COND. THICKNESS	0
$X_f{}^\circ C$	FIELD TEMP IN °C	75
ρ_f	RESISTIVITY OF ROTOR WINDING AT 20°C COLD	.68
	NO LOAD SAT.	1
F & W	FRICTION & WINDAGE LOSS	0

TABLE 3. SUMMARY OF DESIGN CALCULATIONS
SALIENT POLE (OUTPUT - GEN. DATA VS COMPUTER)

		GEN. DATA	COMP. PGM.
STATOR			
ℓ_s	SOLID CORE LENGTH	-	6.175
h_c	DEPTH BELOW SLOTS	-	.850
τ_s	STATOR SLOT PITCH	.393	.393
τ_s 1/3	STATOR SLOT PITCH 1/3 DIST. UP	-	.405
K_{SK}	SKEW FACTOR	.975	.980
K_d	DISTRIBUTION FACTOR	.966	.960
K_p	PITCH FACTOR	.866	.866
n_e	TOTAL EFFECTIVE CONDUCTORS	124.801	122.199
a_c	CONDUCTOR AREA OF STATOR WINDING	-	.002
S_S	CURRENT DENSITY	4270.0	4244.650
ℓ_t	1/2 MEAN TURN	-	9.099
R_{SPH}	COLD STATOR RESISTANCE/PHASE	-	.012
R_{SPH}	HOT STATOR RESISTANCE/PHASE	.015	.0147
EF_{top}	EDDY FACTOR TOP	-	1.0
EF_{bot}	EDDY FACTOR BOTTOM	-	1.0
λ_i	SLOT LEAKAGE PERMEANCE	21.10	11.967
λ_E	END WINDING FLUX LEAKAGE PERMEANCE	1.241	1.324
	WT. OF STATOR COPPER	-	10.305
	WT. OF STATOR IRON	-	95.319
ROTOR			
τ_p	POLE PITCH	1.767	1.767
a_p	POLE AREA	4.630	4.531
$\tau_{e\ell}$	POLE END LEAKAGE PERMEANCE	-	.307
$\tau_{t\ell}$	POLE TIP LEAKAGE PERMEANCE	-	1.045
$\tau_{s\ell}$	POLE SIDE LEAKAGE PERMEANCE	-	1.854
a_{cf}	AREA OF CONDUCTOR	-	.008
R_f	COLD FIELD RESISTANCE AT 20°C	1.50	1.773
R_f	HOT FIELD RESISTANCE AT X°C	-	2.162
	WT. OF FIELD COPPER	-	54.976
	WT. OF ROTOR IRON	-	259.899
V_r	PERIPHERAL SPEED OF ROTOR	-	7037.310
TIME CONSTANTS			
T'_{do}	OPEN CIRCUIT TIME CONSTANT	-	.363
T_a	ARMATURE TIME CONSTANT	-	.002
T'_d	TRANSIENT TIME CONSTANT	-	.102
T''_d	SUBTRANSIENT TIME CONSTANT	-	.005
F_{sc}	SHORT CIRCUIT AMPERE TURNS	250.0	221.390
S_{CR}	SHORT CIRCUIT RATIO	2.221	2.760
GAP			
K_s	CARTER COEFFICIENT	-	1.148
	AIR GAP AREA	276.0	275.710
λ_a	AIR GAP PERMEANCE	89.8	89.250
g_e	EFFECTIVE GAP	.040	.040

TABLE 3. SALIENT POLE (OUTPUT - GEN. DATA VS COMPUTER) - CONTINUED

			GEN. DATA		COMP. PGM.
CONSTANTS					
C_1	FUND/MAX OF FIELD FLUX		1.137		1.189
C_W	WINDING CONSTANT		.445		.466
C_P	POLE CONSTANT		.735		.803
L_E	END EXTENSION LENGTH		-		2.599
C_m	DEMAGNETIZING FACTOR		.840		.823
C_q	CROSS MAGNETIZING FACTOR		-		.517
REACTANCE					
A	AMPERE CONDUCTORS PER INCH		-		305.788
X	REACTANCE FACTOR		.449		.439
X_ℓ	LEAKAGE REACTANCE		-		5.838
X_{ad}	REACTANCE OF ARMATURE REACTION		.385		38.380
X_{aq}	QUADRATURE REACTANCE		.204		20.260
X_d	SYNCHRONOUS REACTANCE		.485		44.224
X_q	QUAD-AXIS SYNCHRONOUS REACTANCE		.304		26.105
X_f	FIELD LEAKAGE REACTANCE		.073		8.266
L_f	FIELD SELF INDUCTANCE	P.U.	.229	%	.643
$X_{D\phi}$	DAMPER LEAKAGE REACTANCE DIRECT		.041		3.302
X_{D8}	DAMPER LEAKAGE REACTANCE QUADRATURE		.028		2.309
X'_{du}	UNSAT. TRANS. REACTANCE		.173		14.105
X'_d	SAT. TRANS. REACTANCE		.152		12.412
X''_d	SUB. TRANS. REACT. DIRECT AX.		.141		9.140
X''_8	SUB. TRANS. REACT. QUAD AX.		.124		8.148
X_2	NEG. SEQUENCE REACTANCE		.133		8.644
X_o	ZERO SEQUENCE REACTANCE		.061		.626
MAGNETIZATION					
ϕ_t	TOTAL FLUX		11530.0		10950.680
ϕ_p	FLUX PER POLE		380.0		366.351
B_g	GAP DENSITY		41.80		39.710
B_t	TOOTH DENSITY		92.50		93.630
B_c	CORE DENSITY		34.00		34.890
F_T	STATOR TOOTH AMPERE TURNS		-		21.770
F_c	STATOR CORE AMPERE TURNS		-		1.210
F_g	AIR-GAP AMPERE-TURNS		524.00		500.600

TABLE 4. AC POWER REQUIREMENTS

ITEM	MIL-STD-704B	MIL-STD-704C	MIL-G-21480	BREADBOARD TEST RESULTS
1	Line-neutral voltage 115/200	same	same	Line to neutral voltage 113 volts no-load
2	Nominal frequency 400HZ	same	Does not apply	Nominal frequency 400HZ
3	Alternate line-neutral 230/400	same	same	Alternate voltage 230 volts L-N
4	Steady state phase volt 108 - 118	same	112.5 - 117.5 volts	Steady state voltage 113 volts
5	Emergency mode phase volt 102 - 124	104 - 122	Does not apply	No test
6	Voltage Unbalance less than 3 volts	same	VOLTAGE/PHASE TESTS	VOLTAGE AND PHASE UNBALANCE TESTS
7	Voltage phase difference 120° ± 2°	116° - 124°	CONDITION / PHASE DISPLACEMENT / PHASE UNBALANCE Balanced load / 120 ± .5° / .5% 1, 1/6, 1/2 unbal loads / 120 ± 4° / 4% 1, 1/3, 1/3 unbal loads / 120 ± 2° / 2% 1, 2/3, 2/3 unbal loads / 120 ± 1° / 1%	CONDITION / VOLTAGE UNBALANCE / PHASE DISPLACEMENT Balanced load / .4 volts / 120 ± 1.3° 1, 1/6, 1/6 unbal loads / OUT OF SPEC 1, 1/3, 1/3 unbal loads / 8.4 volts / 120 ± 2.8° 1, 2/3, 2/3 unbal loads / 5.2 volts / 120 ± 2.3° 15% unbalance / .7 volts / 120 ± 1.15°
8	Phase sequence A-B-C	same	Same ($T_1 - T_2 - T_3 - T_4$)	Phase sequence A-B-C
9	AC waveform distortion not to exceed .05	same	Any single harmonic not to exceed 3%	AC waveform distortion factor .0094
10	AC distortion spectrum (see Figure)	same	Does not apply	Did not exceed spectrum
11	Crest factor not to exceed 1.41 ± .10	1.31 - 1.51	Crest factor 1.41 ± 10%	Crest factor 1.38 - 1.43
12	D.C. component not to exceed ± .10 V	same	Not specified	No D.C. component
13	Waveform shall be within the band V(± .071 + sinθ), where V is max value of equivalent sin wave and θ is the phase angle	Requirement removed	Does not apply	Requirement removed
14	Amplitude modulation components resulting from all modulating influences shall not exceed .62 volts over range 400 ± 60HZ	Requirement removed	Modulation voltage shall not exceed an amplitude of 3.3 volts p-p	Requirement removed
15	System frequency 400 ± 5HZ a. Helicopters 400 ± 20HZ b. Emergency Move 400 ± 40HZ	393 - 407HZ 360 - 440HZ	Does not apply	System frequency transient 400 ± 2HZ
16	Frequency deviation shall not exceed limits of frequency figure	same	Does not apply	Did not test

TABLE 4. AC POWER REQUIREMENTS - Continued

ITEM	MIL-STD-704B	MIL-STD-704C	MIL-G-21480	BREADBOARD TEST RESULTS
17	Frequency drift shall not exceed 15HZ/min	same	Does not apply	Drift of over 15HZ/min due to environment change/stabilized with constant climate
18	Voltage surges shall not exceed limits of figure - 80 milliseconds	80 MSEC recovery	100 milliseconds recovery	Voltage surge recovery time - 64 milliseconds
19	Voltage spike - equipment shall be capable of withstanding spike of: ± 250 volts, duration less than 100 nanosec rise time, 2 nanosec, energy .01youles frequency not greater than 10 MHZ	Requirement removed	Does not apply	Requirement removed
20	Frequency transient limits a. Transient 400 ± 25HZ b. Returning within 400 ± 20HZ in 1 sec c. Returning within 400 ± 10HZ in 15 sec	See AC frequency transient envelope	Does not apply	Frequency transient 400 ± 12HZ
21	Rate of frequency shall not exceed 500HZ/SEC for period greater than 15 milliseconds (7.5HZ)	same	Does not apply	Rate of change did not last longer than 3 cycles equal to 7.5 milliseconds
22	AC over and under voltage values shall not exceed value in Figure - shall not exceed 180 volts in 80 milliseconds	same	Overvoltage shall not esceed 183 volts longer than 110 milliseconds (see curve) a. Undervoltage - system shall be disconnected from load when voltage drops below 90 volts and remains in excess of 5 seconds	Overvoltage shutdown: 150 volts Undervoltage shutdown: 95 volts
23	Out of tolerance frequency shall not exceed ± 25HZ for more than 5 seconds, never to exceed 480HZ	See over/under frequency file	Underfrequency - system shall be disconnected when frequency less than 370HZ is impressed on the load	Overfrequency shutdown: - Underfrequency shutdown: 370HZ
24			Feeder Fault - system shall provide for the generator to be deenergized and disconnected from bus when fault current exceeds .4 per unit for system below 40KVA	System deenergized within limits
25			Load Capacity - generating system shall be capable of delivering a minimum of 100% full load at .75 lagging - 1.0 power factor continuously. The system shall be capable of delivering 150% of rated load .75 lagging - 1.0 power factor for two minutes, and 200% full load at .75 power factor for five seconds.	System capacity: 100% full load .75 lagging PF continuous at 1 PF could not analyze 150% load test could not analyze 200% load test

IV. DISCUSSION OF RESULTS

A. GENERAL. Presently the Navy is developing a program to replace existing Mobile Electric Power Plants. The units to be replaced are the NC-8A and the NC-2A, two commonly used MEPPs that were built to the requirements of MIL-STD-704A. These units are known to have high overall failure rates, low maintainability, and a Mean-Time-Between Failure (MTBF) below 50 hours. To provide the new generator power capability required by MIL-STD-704C and provide a higher reliability and maintainability of the total unit, a new MEPP is to be developed.

The heart of the new MEPP will be a diesel driven generator using a brushless exciter to eliminate the maintenance requirement of brushes. An exploratory R&D program to develop a generator capable of supplying aircraft utilization equipment power per MIL-STD-704C has been completed.

B. APPROACH AND SPECIFIC RESULTS. In the generator development program, a generator was obtained with a diesel engine on a test bed. The system was modified for laboratory instrumentation and various generator test equipment was purchased to analyze the system's output under various loading conditions.

1. To make an analytical study, a computer program was developed to make generator design calculations and predicted output characteristics. This program was helpful in that from the physical dimensions of the generator, many of the electrical parameters can be calculated. Output data such as line current, field current, field voltage, flux densities and various losses can be obtained at 50%, 100%, 150% and 200% of full load. This data can be obtained under any power factor or any loading conditions. For this program data was obtained at .8 lagging power factor; see Table 1 for results.

2. Results of the program were tabulated and compared to the requirements of MIL-STD-704C. Using a step by step approach to each requirement of MIL-STD-704C, every requirement within the power system Standard was compared to the output characteristics of the generator, see Table 4. Voltage regulation, voltage unbalance, voltage transients, harmonics, frequency drift and frequency modulation are some of the major parameters that were analyzed. As an example of the work that was done, in the case of voltage unbalance, it was observed that the voltage unbalance during worst case conditions did not comply with the requirements of MIL-STD-704C. Calculations were made to alter the generator's characteristics under load unbalance and proper recommendations were made to correct the problem.

3. As each portion of the new standard was analyzed, it was observed that many characteristics of the generator complied with the requirements of MIL-STD-704C as it existed and only a few parameters required moderate modifications. Often, a resistance or minor winding change was all that was necessary to make the system conform to the proper specification. These calculations may be seen in the appendices of this report.

4. In other areas, modifications were more difficult, as in the case of voltage transient time of the generator. The time for the power system

to recover from no load to full is dependent on generator field and exciter times constants as well as voltage regulator parameters. To deal with this problem, several computer programs were developed to solve the mathematical equation that represents the transfer functions of the generator and control circuits. The program was designed to solve the equations and print out generator phase voltage, field voltage and exciter current for increments of time. Along with the list of output parameters, the program plots a curve of phase voltage for increments of time when a step load is applied to the generator's terminals, Figures 8, 9, and 10. From this print out, a determination could be made as to what the time constants were within the generator and what electrical characteristics a voltage regulator would be responsible for.

5. The information obtained from the computer program was then the input data for a concurrent project "Application of Microcomputer to Mobile Electric Power Plants". In this program, a voltage regulator and frequency control unit has been developed to use with the engine generator. Using the present engine-generator set with the microcomputer circuits, a power system that conforms to MIL-STD-704C has been achieved.

6. To verify the validity of the computer program results, a generator test program was developed. As stated previously, the engine generator was modified for laboratory instrumentation. An extensive test program was employed using the prescribed method of Test Standard MIL-STD-705B. Using this test standard as a guide, a step by step analysis of the generator characteristics were made until all of the requirement of MIL-STD-704C were investigated.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS. There is a current program within the Navy to replace existing Mobile Electric Power Plants. Existing units do not comply with the new standard of power and are overdue for retirement. To develop a Mobile Electric Power Plant, several major programs were deployed - one of those subtasks being a 30 kilowatt diesel driven generator development program.

This program progressed through a sequence of feasibility studies, theoretical calculations, breadboard building and test/evaluations analyses.

After completion of all the development phases, results indicate that the DOD diesel driven generator, MEPP 114A, is an acceptable unit to be used in a Mobile Electric Power Plant.

1. Data obtained from the feasibility study has indicated that the generator has a mean-time-between-failures of 500 hours.

2. From results obtained from several computer programs, the generator has the proper electrical parameters to comply with MIL-STD-704C.

3. Test and evaluation data substantiate program calculations as to the ability of the generator to comply with the electrical and logistical requirements of the Navy.

B. RECOMMENDATIONS. As stated above, the DOD diesel driven generator complies with the requirement of MIL-STD-704C.

1. It is recommended that this generator, made by Electric Machine, be used as the power source in any new or retrofitted Mobile Electric Power Plant that is to be used by the fleet.

2. The 90 horsepower diesel Hercules/White engine presently used with the test bed is an adequate prime mover for the generator and should be used in any new or retrofitted MEPP.

a. The present engine-generator package has the proper flywheel, bearing alignment and minimal torsional vibration.

3. The existing hydraulic governor system does comply with the frequency requirements but has a poor mean-time-between-failures rate. It is recommended that this system be changed with a new system that complies with MIL-STD-704C and has a better MTBF.

4. While the various control circuits in the present test bed could be reworked to comply with MIL-STD-704C, it is recommended that a new design package be employed. A concurrent program using a microcomputer is now in progress and would be a good candidate to replace existing electronics.

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VII. FIGURES

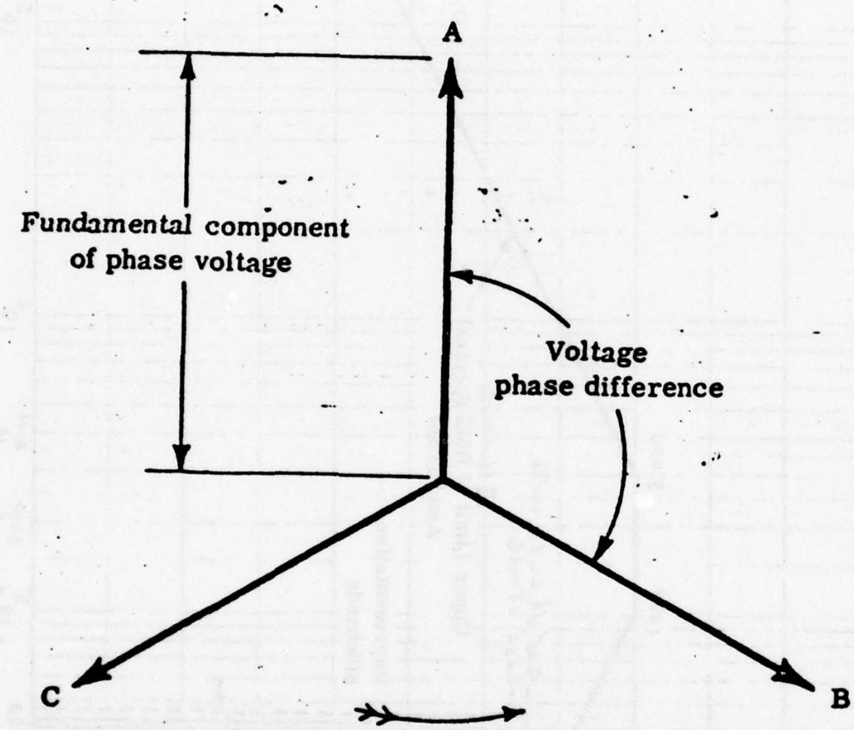


FIGURE 1. PHASOR DIAGRAM SHOWING REQUIRED PHASE SEQUENCE RELATIONSHIP

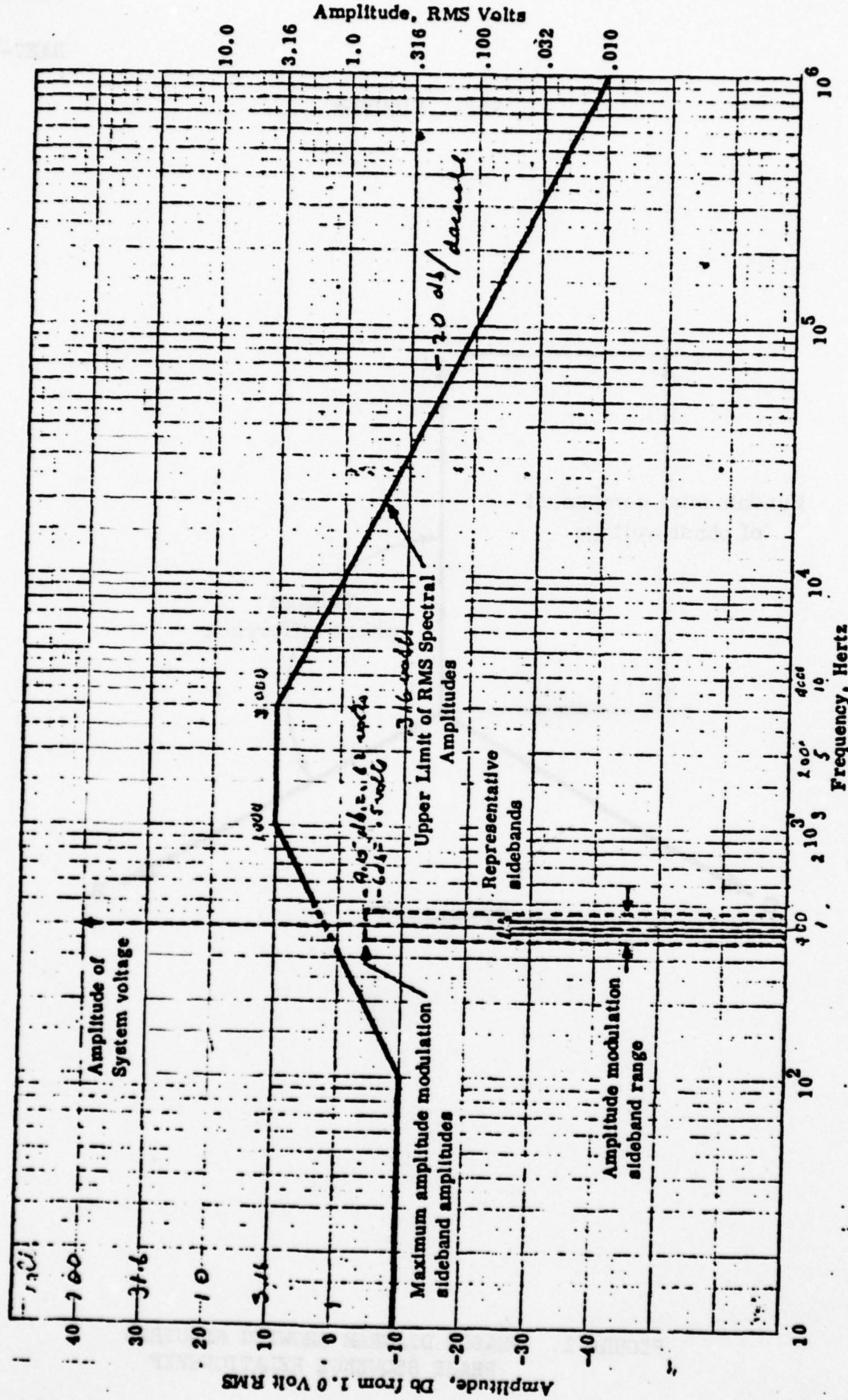


FIGURE 2. DISTORTION SPECTRUM OF AC VOLTAGE

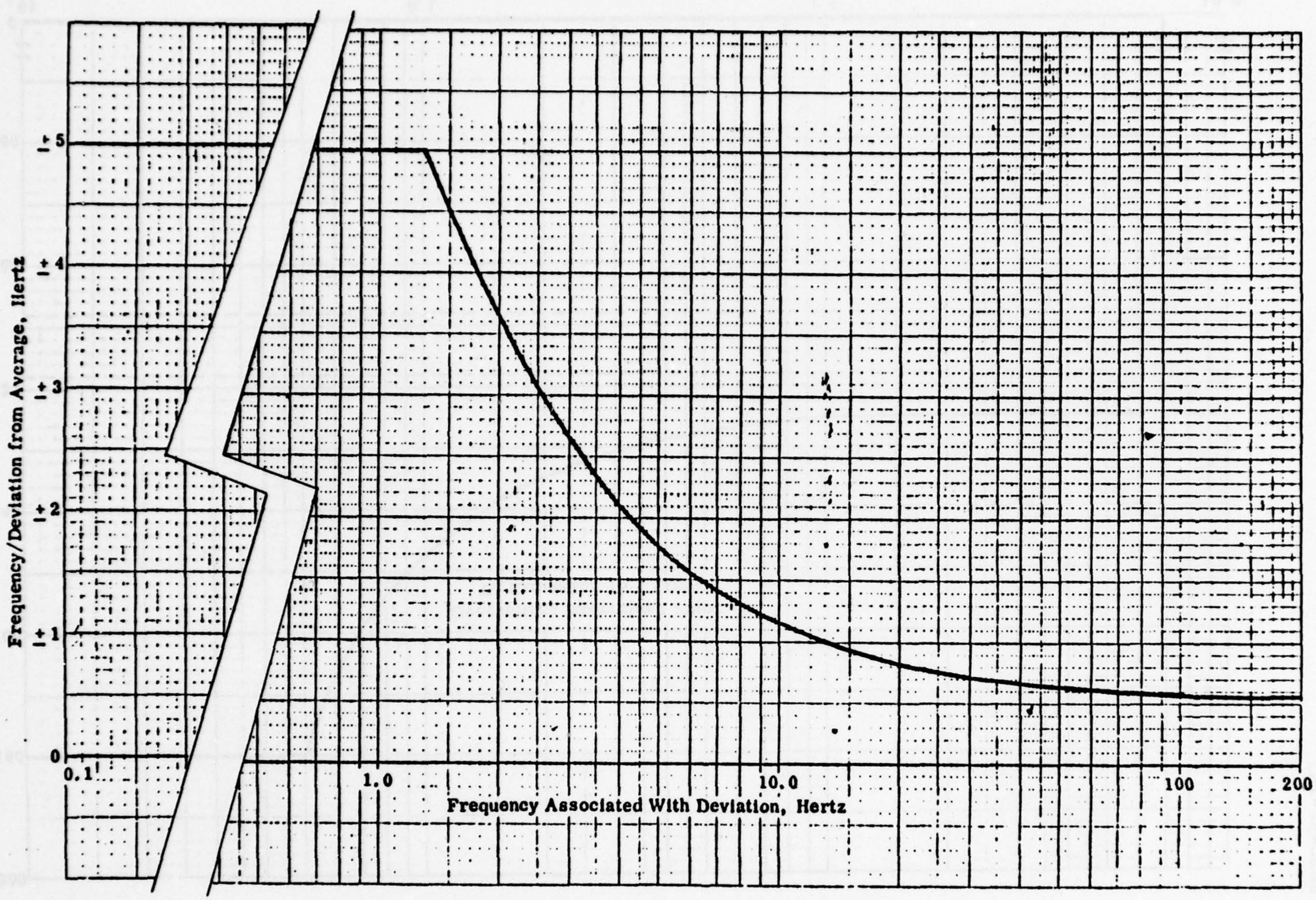


FIGURE 3. LIMITS OF FREQUENCY DEVIATION

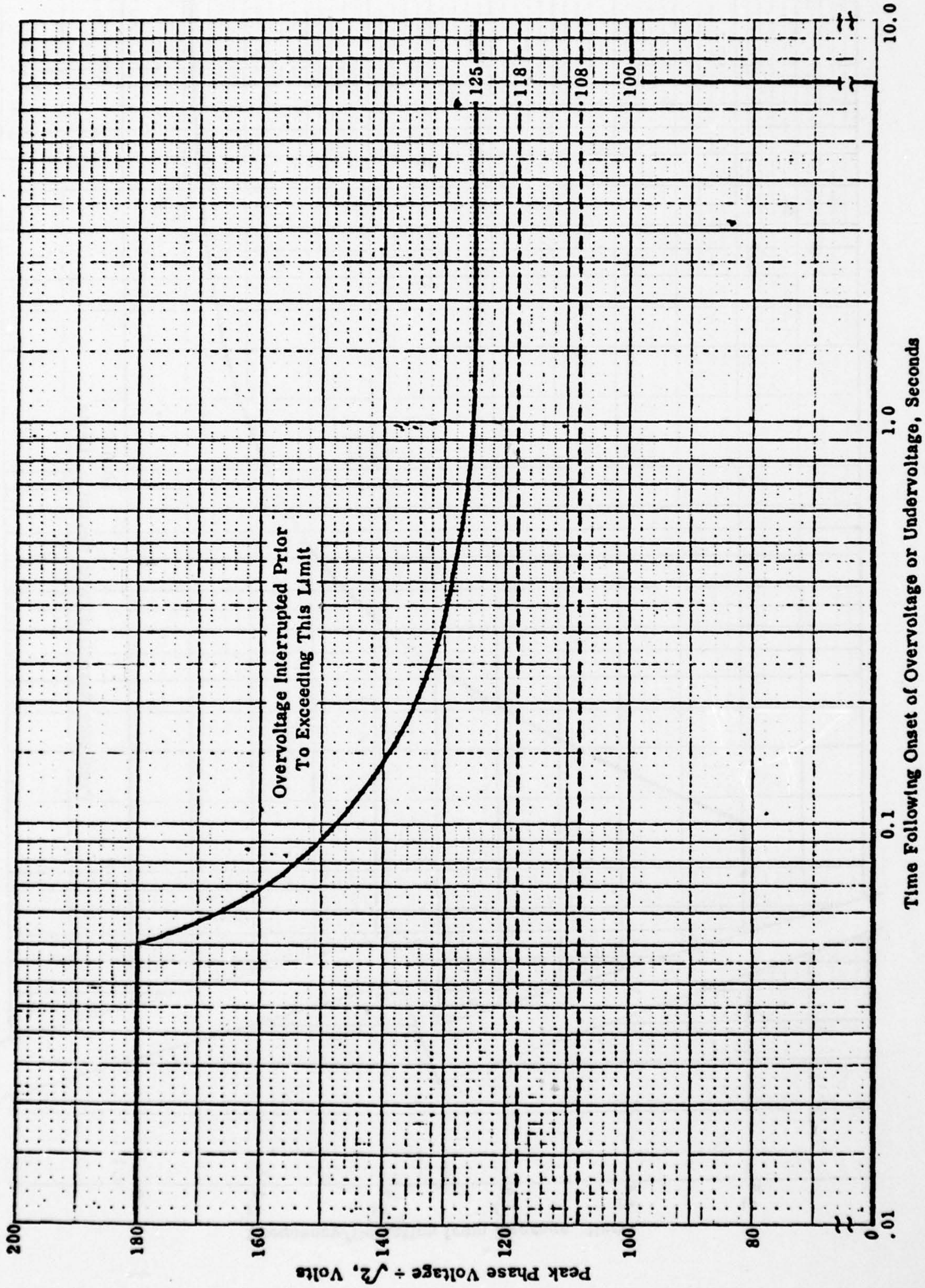


FIGURE 4. AC LIMITS FOR CONSTANT OVERVOLTAGE OR UNDERVOLTAGE

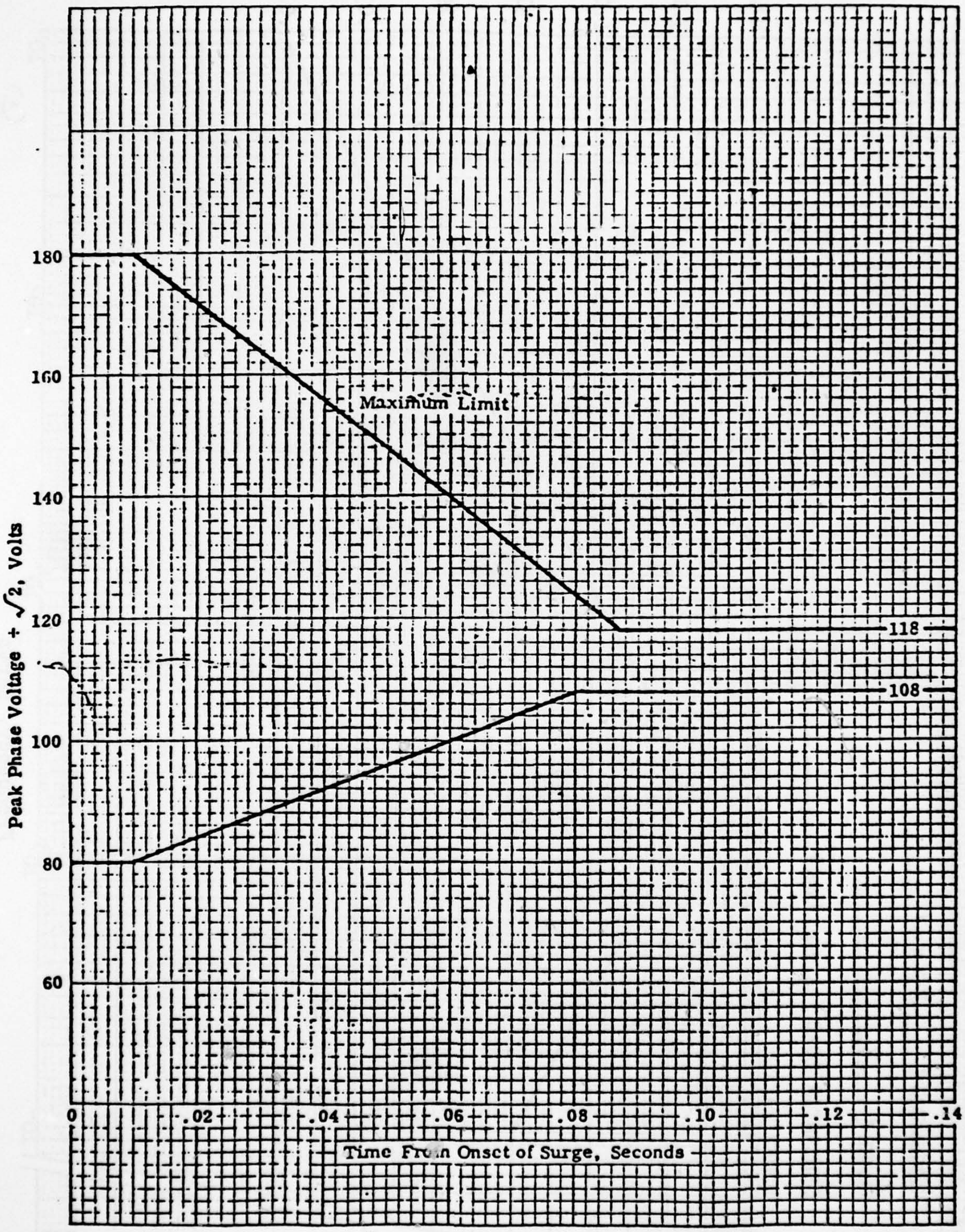


FIGURE 5. ENVELOPE OF AC VOLTAGE SURGE

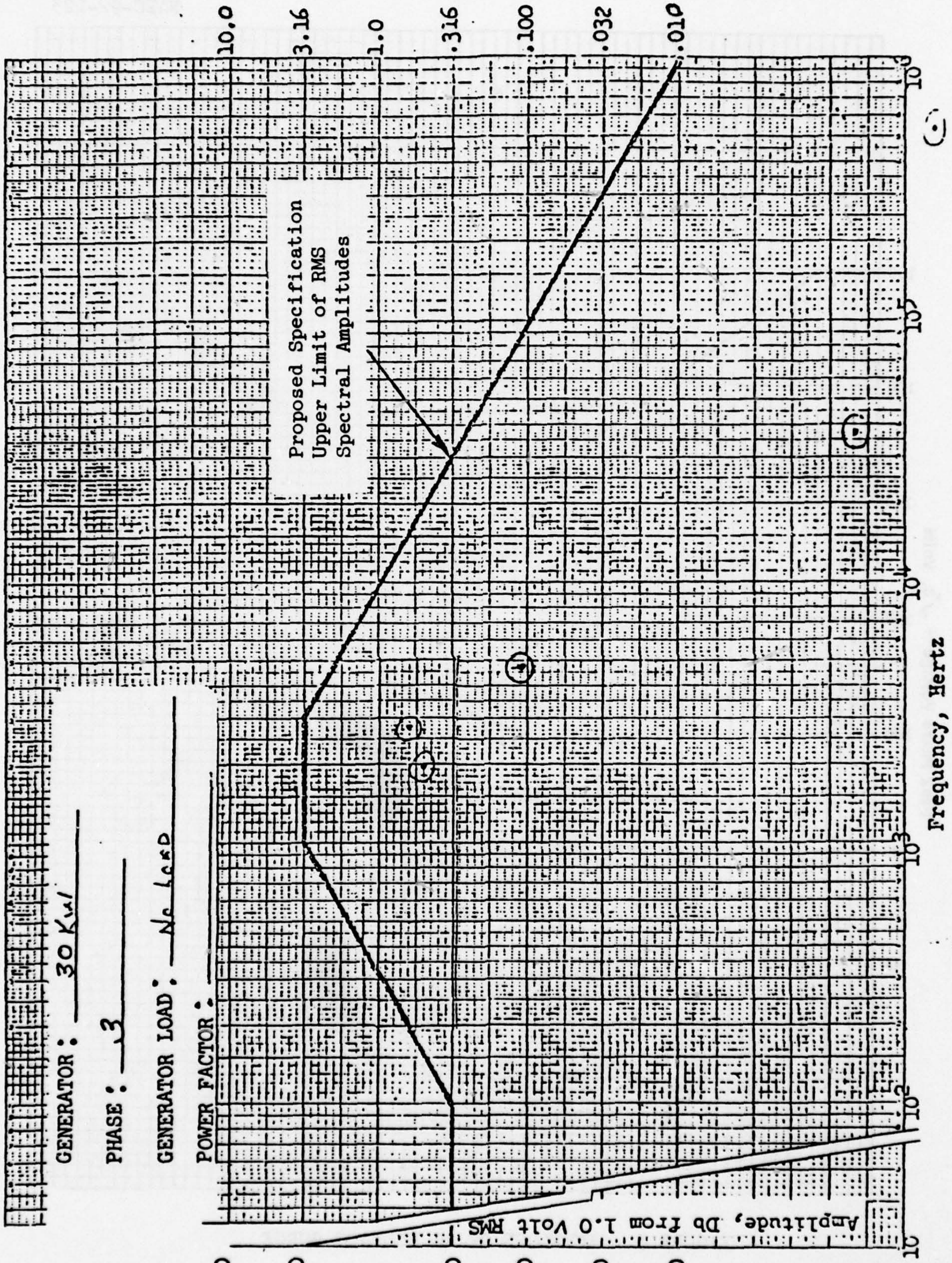


FIGURE 6. DISTORTION SPECTRUM OF AC VOLTAGE

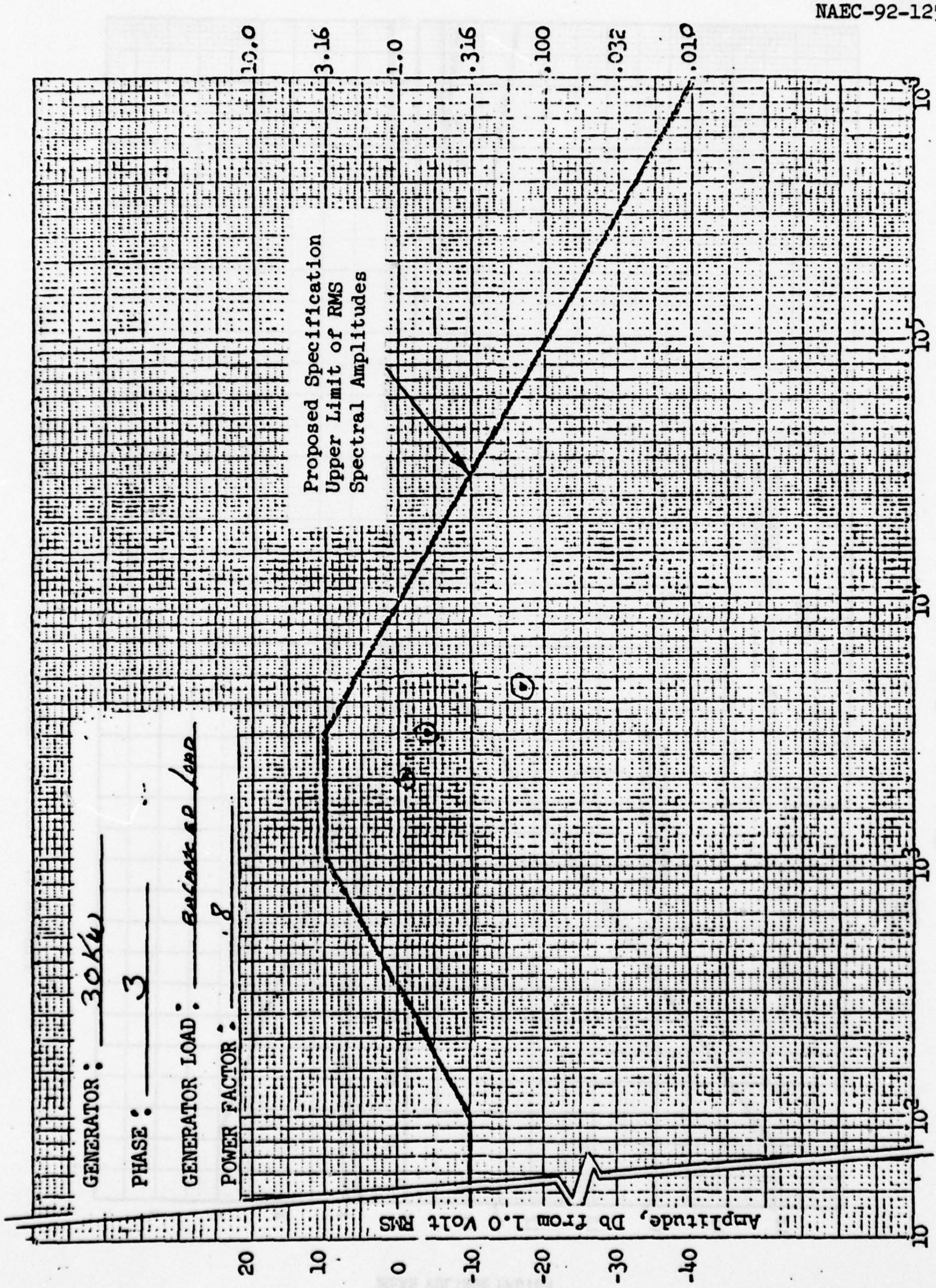


FIGURE 7. DISTORTION SPECTRUM OF AC VOLTAGE

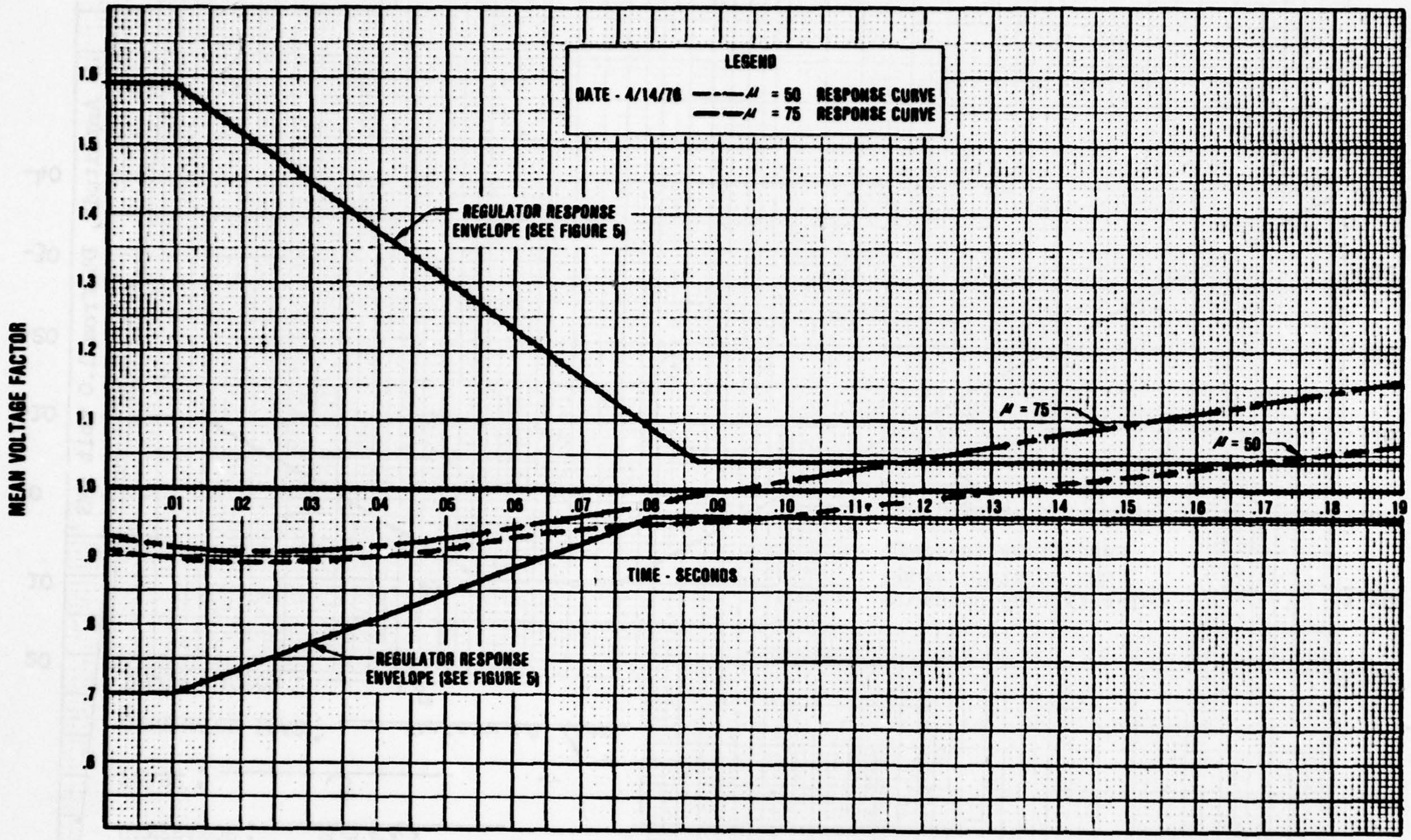


FIGURE 8. VOLTAGE REGULATOR RESPONSE - PROPORTIONAL TYPE

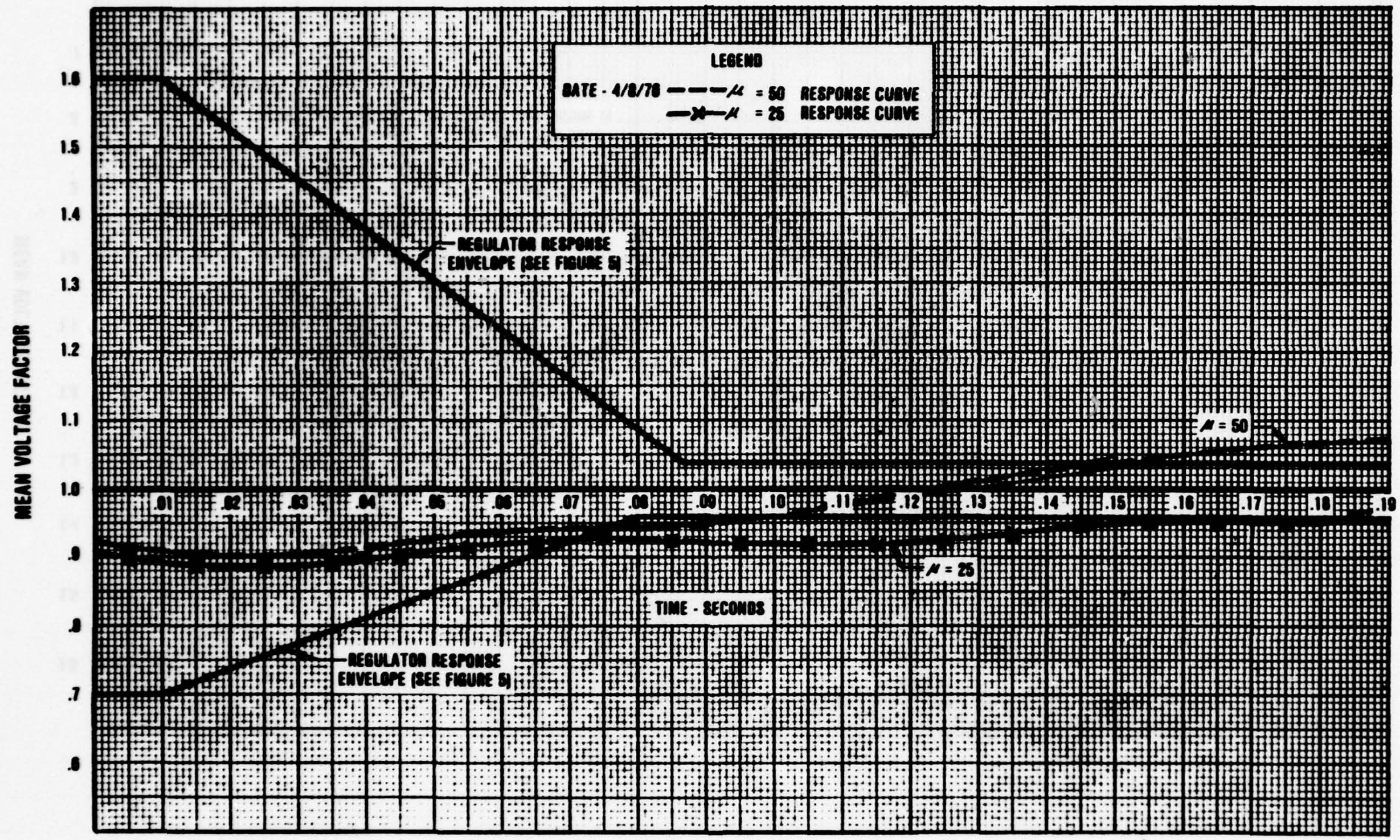


FIGURE 9. VOLTAGE REGULATOR RESPONSE CURVE - INTEGRAL TYPE
GAIN = 50 GAIN = 25

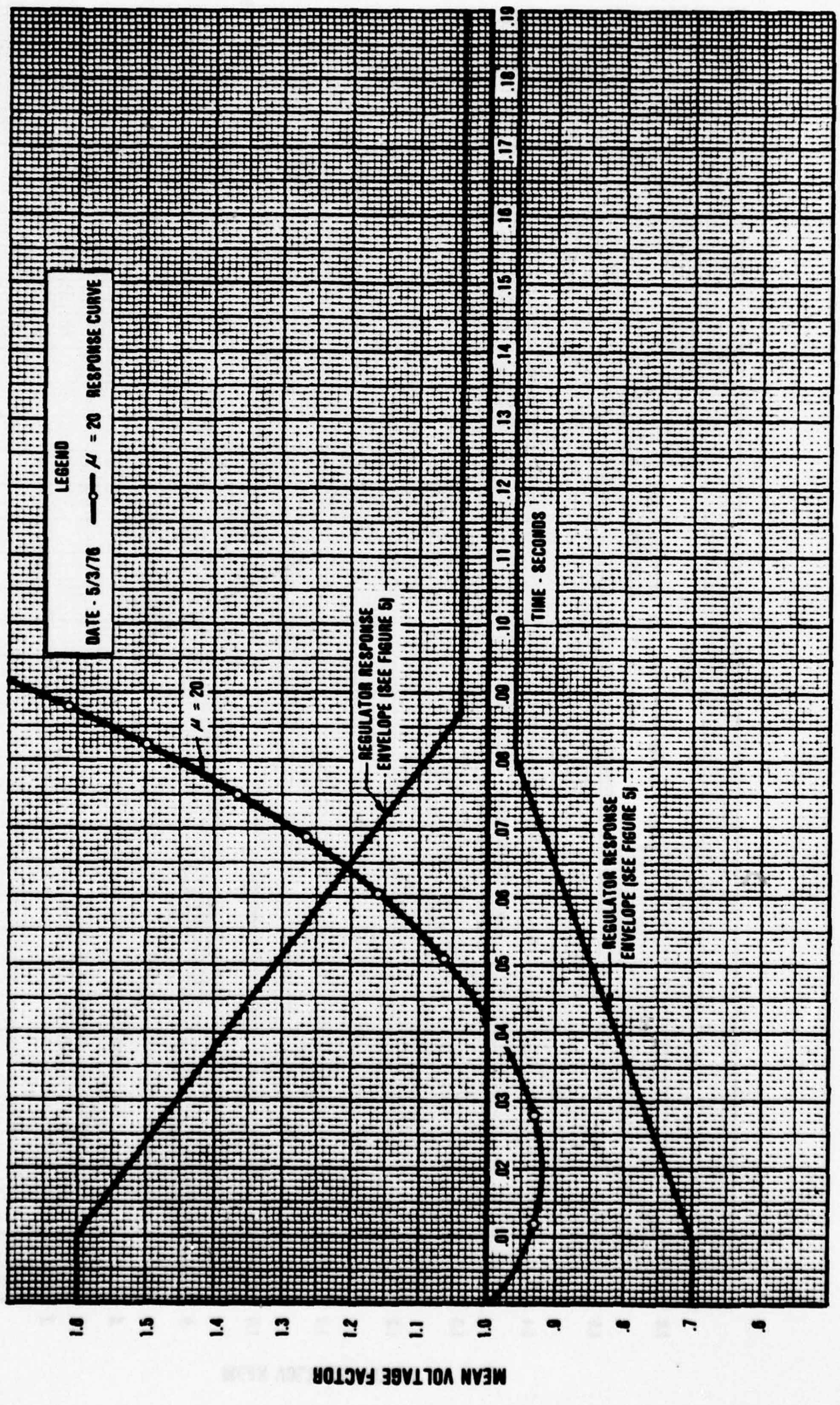


FIGURE 10. VOLTAGE REGULATOR RESPONSE CURVE - INTEGRAL TYPE
GAIN = 20

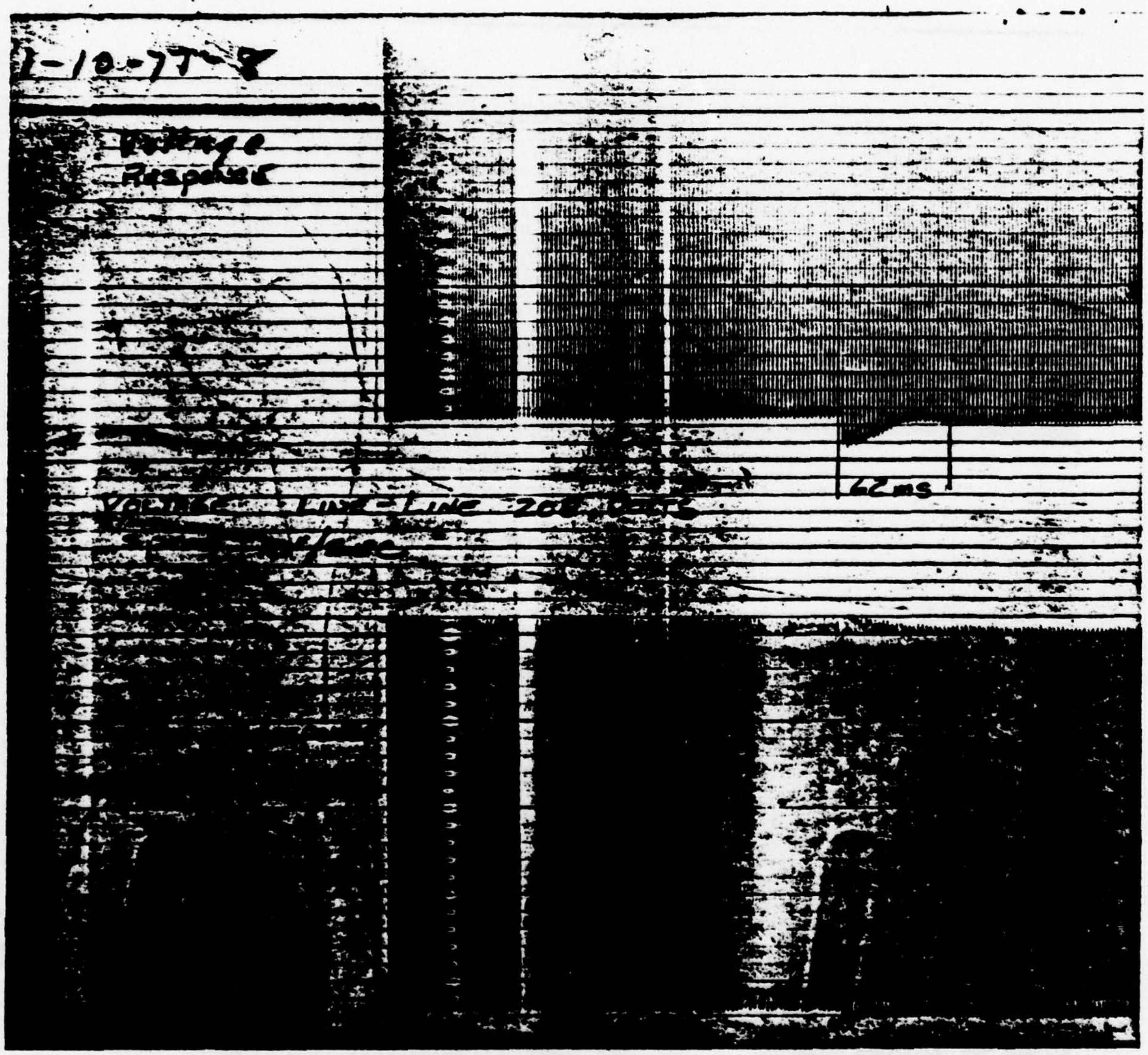


FIGURE 11. TEST DATA - VOLTAGE RESPONSE CURVE/APPLICATION OF LOAD

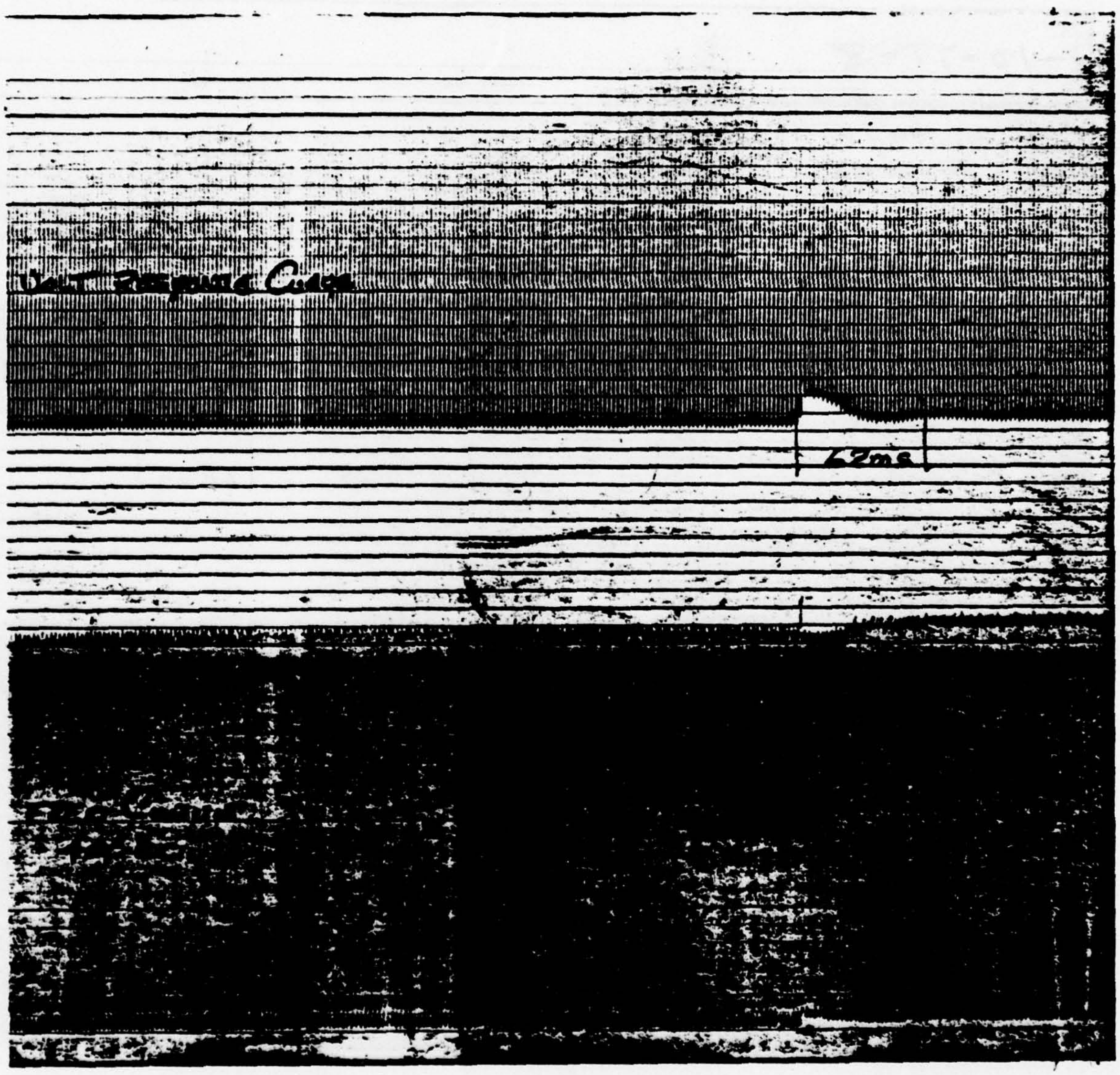


FIGURE 12. TEST DATA - VOLTAGE RESPONSE CURVE/LOAD REMOVED

VIII. APPENDIXES

APPENDIX A

NO LOAD WAVE SHAPE OF SALIENT POLE A.C. GENERATORS

CALCULATION OF NO-LOAD WAVE SHAPE OF SALIENT-POLE A.C. GENERATORS

SEE REF (d) AND (e)

FOR UNIFORM AIR GAP

$$C_{np} = \frac{4}{n\pi} \sin \frac{n\alpha\pi}{2}$$

$$C_{ni} = 4\left(\frac{g_n}{g_x}\right)\left[\frac{1-\alpha}{4K^2+(1-\alpha^2)\pi^2 n^2}\right]\left[2K\cos\frac{n\alpha\pi}{2}\,\mathrm{Ctnh}\,K-(1-\alpha)n\pi\sin\frac{n\alpha\pi}{2}\right]$$

WHERE $K = .768\left[\frac{1-\alpha}{2}\left(\frac{\tau}{g_r}\right)\right]^{.617}\tan^{-1}\left[\left(\frac{1-\alpha}{2}\right)\left(\frac{\tau}{g_r}\right)\right]$

$$\text{AMOUNT OF HARMONIC CONTENT} = \frac{C_{ni}+C_{np}}{C_1}\left[\frac{K_d \cdot K_p \cdot K_{sk}}{K_{d_1} \cdot K_{p_1} \cdot K_{sk_1}}\right]$$

WHERE $K_{dn} = \frac{1}{6\cos(100n)}$

$$K_{pn} = \sin 60n$$

$$K_{sinn} = \frac{9\sin 20n}{n\pi}$$

VOLTAGE = HARMONIC CONTENT (115 VOLTS)

$$DB = 20\log_{10} V$$

$$FREQ = 400n$$

n	Cp	Cn	Content	Voltage	DB	Freq
1	1.138	.0516	.999	114.89	41.21	400
2	.509	-.1163	.057	6.57	16.35	800
5	-.173	.1293	-.004	.55	- 5.20	2K
7	.181	-.0620	-.004	.56	- 4.89	2.8K
9	-.073	-.0205	0	0	0	3.6K
11	-.043	.0793	-.0009	-10.0	-19.23	4.4K
97	.007	-.0062	.000004	.0004	-66.74	38.8K
997	.001	.0012	.000001	.0001	-78.78	39.8K
2497	.0003	-.0003	0	0	0	998.8K

THE RESULTS OF THESE CALCULATIONS CAN BE SEEN GRAPHICALLY ON FIGURE 6 OF THIS REPORT

APPENDIX B

VOLTAGE HARMONICS OF SALIENT POLE GENERATOR UNDER BALANCE 3-PHASE LOAD CALCULATIONS

VOLTAGE HARMONICS OF SALIENT-POLE GENERATORS UNDER BALANCED 3-PHASE LOADS

SEE REF (c) AND (f)

AT .8 POWER-FACTOR LAG

$$h_n = \sqrt{\left[(.9)\left(1+\frac{X_d}{Z_L}\right)\frac{C_n}{C_1} - \frac{X_{ad}}{C_m Z_L}\,\frac{1.25\left(\frac{X_q}{Z_L}+.6\right)}{\sqrt{1+1.25\left(\frac{X_q}{Z_L}+.6\right)}}\,\frac{C_{nad}}{C_1}\right]^2 + \left[\frac{X_{ad}}{C_m Z_L}\,\frac{1.}{\sqrt{1+\left[1.25\left(\frac{X_q}{Z_L}+.06\right)\right]^2}}\cdot\frac{C_{naq}}{C_1}\right]^2}$$

$$H_n = \frac{h_n}{1+K_n\left(\frac{X_d''+X_q}{Z_L}\right)}$$

$$\text{CONTENT} = H_n \frac{K_d K_p K_s}{K}$$

$$\text{VOLTAGE} = (115)\ \text{CONTENT}$$

$$\text{DB} = 20 \operatorname{Log}_{10} V$$

$$\text{FREQ} = n(400)$$

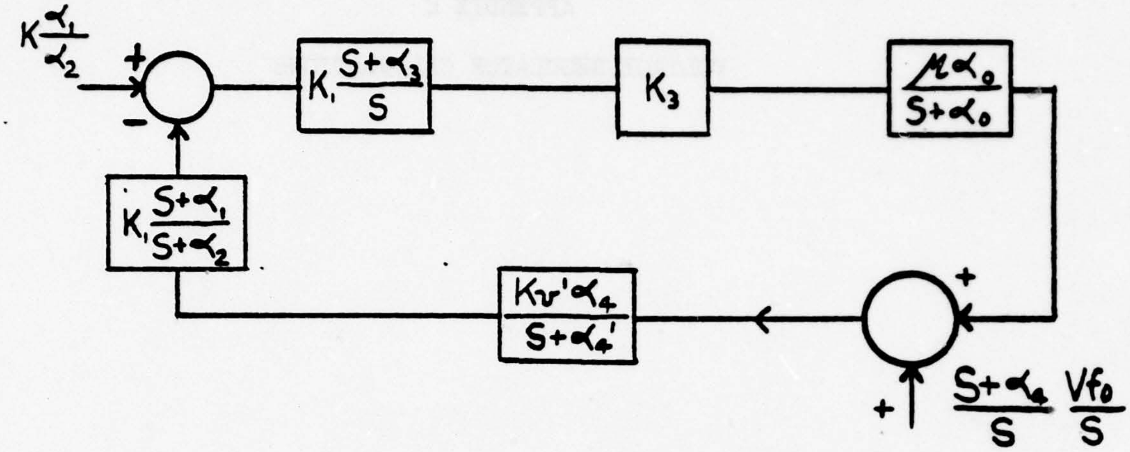
n	hn	Hn	Content	Voltage	DB	Freq
3	.2455	.1936	0	0	0	1.2K
5	.0804	.0626	.0081	.9338	-.5949	2.0K
7	.1283	.0996	.0049	.5667	-4.932	2.8K
9	.1073	.0831	0	0	0	3.6K
11	.0465	.0359	.0011	-.1303	-17.700	4.4K

THE RESULTS OF THESE CALCULATIONS CAN BE SEEN GRAPHICALLY ON FIGURE 7 OF THIS REPORT

APPENDIX C

VOLTAGE REGULATOR CALCULATIONS

VOLTAGE REGULATOR CALCULATIONS



$$\left\{K\left[\frac{\alpha_1 V_{des}}{\alpha_2 S} - \frac{S+\alpha_1}{S+\alpha_2}X\right]K_2\frac{S+\alpha_3}{S}XK_3\frac{\mu\alpha_0}{S+\alpha_0} + \frac{(S+\alpha_4)Vf_0}{S}\right\}\frac{Kv'\alpha_4}{S+\alpha_4} = X_1$$

$$\left\{K\frac{(S+\alpha_3)\mu\alpha_0}{S(S+\alpha_0)}\left[\frac{\alpha_1}{\alpha_2}\frac{V_{des}}{S} - \frac{S+\alpha_1}{S+\alpha_2}X_1\right] + \frac{S+\alpha_4 Vf_0}{S}\right\}\frac{Kv'\alpha_4}{S+\alpha_4} = X_1$$

$$\left(\frac{\mu KKv'\alpha_0\alpha_4\cancel{(S+\alpha_3)}(S+\alpha_1)}{S\cancel{(S+\alpha_0)}(S+\alpha_2)(S+\alpha_4')}+1\right)X_1 = \frac{\mu K\alpha_0\alpha_4\cancel{(S+\alpha_3)}}{S\cancel{(S+\alpha_0)}(S+\alpha_4')}\frac{\alpha_1}{\alpha_2}\frac{V_{des}}{S} + \frac{Kv'\alpha_4^{(S+\alpha_4)}}{S+\alpha_4'}\frac{Vf_0}{S}$$

$$X_1 = \frac{S(S+\alpha_4)(S+\alpha_2)\frac{Vf_0}{S} + \frac{A}{Kv'}\frac{\alpha_1}{\alpha_2}(S+\alpha_2)\frac{V_{des}}{S}}{S(S+\alpha_4')(S+\alpha_2)+A(S+\alpha_1)}$$

$$X_1(S) = \frac{1}{S}\;\frac{S(S+\alpha_4)(S+\alpha_2)+\frac{A}{Kv'}\frac{\alpha_1}{\alpha_2}(S+\alpha_2)}{S(S+\alpha_4)(S+\alpha_2)+A(S+\alpha_1)}$$

$$X_1(S) = \frac{1}{Kv'S} + \frac{a}{S+\beta} + \frac{B(S+\alpha)}{S^2+2\alpha S+\omega_0^2} + \frac{C\omega_1}{S^2+2\alpha S+\omega_0^2}$$

$$X_1(S) = \frac{1}{Kv'S} + \left\{\frac{S^3+(\alpha_4+\alpha_2)S^2+\left(\alpha_2\alpha_4+\frac{A}{Kv'}\frac{\alpha_1}{\alpha_2}\right)S+\frac{A\alpha_1}{Kv'}}{S[S^3+(2\alpha+\beta)S^2+(\omega_0^2+2\alpha\beta)S+\beta\omega_0^2]} - \frac{\frac{1}{Kv'}}{S}\right\}$$

$$X_1(S) = \frac{1}{Kv'S} + \left[\frac{S^{2}\left(1-\frac{1}{Kv'}\right)+S\left(\alpha_4+\alpha_2-\frac{\alpha_2+\alpha_4'}{Kv'}\right)+\left(\alpha_2\alpha_4+\frac{A\alpha_1}{Kv'\alpha_2}-\frac{\alpha_2\alpha_4'+A}{Kv'}\right)+\frac{A\alpha_1}{Kv'}-\frac{\alpha_1 A}{Kv'}}{S(S+\beta)(S^2+2\alpha S+W_o^2)}\right]$$

$$\text{SINCE: }\left(\begin{matrix}\alpha_2+\alpha_4' = 2\alpha+\beta\\ \alpha_4\alpha_2+A = W_o^2+2\alpha\beta\\ \alpha_1 A = W_o^2\beta\end{matrix}\right)$$

$$\therefore X_1(S) = \frac{a(S^2+2\alpha S+W_o^2)+B(S^2+(2+\beta)S+\alpha\beta)+CW_o(S+\beta)}{(S+\beta)(S^2+2\alpha S+W_o^2)} + \frac{1}{Kv'S}$$

$$a+B = 1-\frac{1}{Kv'}$$

$$CW_1+2\alpha a+(\alpha+\beta)B = \alpha_2\left(1-\frac{1}{Kv'}\right)+\alpha_4-\frac{\alpha_4'}{Kv'}$$

$$W_o^2 a+\alpha\beta B+CW_1\beta = \alpha_2\left(\alpha_4-\frac{\alpha_4'}{Kv'}\right)+\frac{A}{Kv'\alpha_2}(\alpha_1-\alpha_2)$$

$$\beta CW_1+2\alpha\beta a+\beta(\alpha+\beta)B = \beta\alpha_2\left(1-\frac{1}{Kv'}\right)+\beta\left(\alpha_4-\frac{\alpha_4'}{Kv'}\right)$$

$$\beta CW_1+W_o^2 a+\beta(\alpha)B = \frac{A}{Kv'}\left(\frac{\alpha_1-\alpha_2}{\alpha_2}\right)+\alpha_2\left(\alpha_4-\frac{\alpha_4'}{Kv'}\right)$$

$$(W_o^2-2\alpha\beta)a-\beta^2 B = (\alpha_2-\beta)\left(\alpha_4-\frac{\alpha_4'}{Kv'}\right)-\beta\alpha_2\left(1-\frac{1}{Kv'}\right)+\frac{A}{Kv'}\,\frac{\alpha_1-\alpha_2}{\alpha_2}$$

$$(W_o^2-2\alpha\beta+\beta^2)a-\beta^2\left(1-\frac{1}{Kv'}\right) = (\alpha_2-\beta)\left(\alpha_4-\frac{\alpha_4'}{Kv'}\right)-\beta\alpha_2\left(1-\frac{1}{Kv'}\right)+\frac{A}{Kv'}\,\frac{\alpha_1-\alpha_2}{\alpha_2}$$

$$a = \frac{(\beta-\alpha_2)\left[\beta\left(1-\frac{1}{Kv'}\right)-\alpha_4+\frac{\alpha_4'}{Kv'}\right]+\frac{A}{Kv'}\,\frac{\alpha_1-\alpha_2}{\alpha_2}}{\beta^2-2\alpha\beta+W_o^2}$$

$$B = 1-\frac{1}{Kv'}-a$$

$$CW_1 = \alpha_2\left(1-\frac{1}{Kv'}\right)+\left(\alpha_4-\frac{\alpha_4'}{Kv'}\right)-\alpha(A+B)-\alpha a-\beta B$$

$$CW_1 = \alpha_2\left(1-\frac{1}{Kv'}\right)+\left(\alpha_4-\frac{\alpha_4'}{Kv'}\right)-\alpha\left(1-\frac{1}{Kv'}\right)-\alpha a-\beta\left(1-\frac{1}{Kv'}\right)+\beta a$$

$$CW_1 = (\alpha_2-\alpha-\beta)\left(1-\frac{1}{Kv'}\right)+\left(\alpha_4-\frac{\alpha_4'}{Kv'}\right)+(\beta-\alpha)a$$

$$CW_1=\left(\alpha_2-\alpha-\beta+\frac{(\beta-\alpha)(\beta-\alpha_2)\beta}{\beta^2-2\alpha\beta+W_o^2}\right)\left(1-\frac{1}{Kv'}\right)+\left[1-\frac{(\beta-\alpha)(\beta-\alpha_2)}{\beta^2-2\alpha\beta+W_o^2}\right]\left(\alpha_4-\frac{\alpha_4'}{Kv'}\right)$$

$$\cancel{-\beta^3}\cancel{+2\alpha\beta^2}-\beta W_o^2-\cancel{\alpha\beta^2}+2\alpha^2\beta-\alpha W_o^2+\alpha_4\beta^2-2\alpha\alpha_2\beta+\alpha_2 W_o^2$$

$$\beta^3-(\alpha+\alpha_2)\beta^2+\alpha\alpha_2\beta$$

$$CW_1=\left\{\alpha_2(W_o^2-\alpha\beta)+2\alpha^2\beta-(\alpha+\beta)W_o^2\right\}\left(1-\frac{1}{Kv'}\right)+\left(W_o^2-\alpha\beta+\alpha_2(\beta-\alpha)\right)$$
$$+\frac{A}{Kv'}\;\frac{\alpha_1-\alpha_2}{\alpha_2}\;\frac{(\beta-\alpha)}{\beta^2-2\alpha\beta+W_o^2}$$

$$a=\frac{\beta(\beta-\alpha_2)\left(1+\frac{1}{Kv'}\right)-(\beta-\alpha_2)\left(\alpha_4\,\frac{\alpha_4'}{Kv'}\right)+\frac{A}{Kv'}\;\frac{\alpha_1-\alpha_2}{\alpha_2}}{\beta^2-2\alpha\beta+W_o^2}$$

$$B=1-\frac{1}{Kv'}-a$$

$$CW_1=\frac{\left[\alpha_2(W_o^2-\alpha\beta)+2\alpha^2\beta-(\alpha+\beta)W_o^2\right]\left(1-\frac{1}{Kv}\right)+\left(W_o^2-\alpha\beta+\alpha_2(\beta-\alpha)\right)\left(\alpha_4-\frac{\alpha_4}{Kv'}\right)+\frac{A}{Kv'}\frac{\alpha_1-\alpha_2}{\alpha_2}(\beta-\alpha)}{\beta^2-2\alpha\beta+W_o^2}$$

$$X_1(t)=\frac{1}{Kv'}\,ae^{-\beta t}+Be^{-\alpha t}\cos W_1t+Ce^{-\alpha t}\sin W_1t$$

$$X_1(\infty)=\frac{1}{Kv'}$$

$$X_1(0)=\frac{1}{Kv'}+a+B=\frac{1}{Kv'}+\left(1-\frac{1}{Kv'}\right)=1$$

$$\frac{dX_1}{dt}=-\alpha_4'X_1+\alpha_4X_2+\alpha_4Vf_o,\qquad X_1(0)=Vf_o=1$$

$$\frac{dX_2}{dt}=\mu K\alpha_0X_3,\qquad X_2(0)=0$$

$$\frac{dX_3}{dt}=-a_1X_1-a_2X_2-\alpha_2X_3+A_0,\qquad X_3(0)=\frac{\alpha_1}{\alpha_2}-Kv'$$

$$(S+\alpha_4')X_1=\alpha_4X_2+(S+\alpha_4)\frac{Vf_o}{S}$$

$$SX_2=\mu K\alpha_0X_3\qquad S(S+\alpha_2)X_2=\mu K\alpha(S+\alpha_2)X_3$$

$$(S+\alpha_2)\chi_3 = -a_1\chi_1 - a_2\chi_2 + \frac{a_0}{S} + \chi_3(0)$$

$$S(S+\alpha_2)\chi_2 = \mu K\alpha_0\left[-a_1\chi_1 - a_2\chi_2 + \frac{a_0}{S} + \chi_3(0)\right]$$

$$S(S+\alpha_2)(S+\alpha_4')\chi_1 = S(S+\alpha_2)\alpha_4\chi_2 + S(S+\alpha_2)(S+\alpha_4)\frac{Vfo}{S}$$

$$S(S+\alpha_2)(S+\alpha_4')\chi_1 = \mu K\alpha_0\alpha_4\left[-a_1\chi_1 - a_2\chi_2 + \frac{a_0}{S} + \chi_3(0)\right] + S(S+\alpha_2)(S+\alpha_4)\frac{Vfo}{S}$$

$$\left\{S(S+\alpha_2)(S+\alpha_4) + \mu K\alpha_0\alpha_4\left[a_1 + a_2\frac{S+\alpha_4'}{\alpha_4}\right]\right\}\chi_1 =$$
$$\mu K\alpha_0\alpha_4\left[a_2\frac{S+\alpha_4}{\alpha_4}\frac{Vfo}{S} + \frac{a_0}{S} + \chi_3(0)\right] + S(S+\alpha_2)(S+\alpha_4)\frac{Vfo}{S}$$

$$\mu K\alpha_0\alpha_4\left[a_1 + a_2\frac{S+\alpha_4'}{\alpha_4}\right] = \mu K\alpha_0\alpha_4 Kv'(S+\alpha_1)$$

$$(1) \qquad a_1 + a_2\frac{\alpha_4'}{\alpha_4} = Kv'\alpha_1$$

$$(2) \qquad \frac{a_2}{\alpha_4} = Kv'$$

$$\frac{a_2Vfo + a_0}{S} + \frac{a_2Vfo}{\alpha_4} + \chi_3(0) = \frac{\alpha_1}{\alpha_2}(S+\alpha_2)\frac{Vdes}{S} = \frac{\alpha_1}{\alpha_2} + \alpha_1\frac{1}{S}$$

$$a_2 = \alpha_4 Kv'$$

$$a_1 = Kv'\alpha_1 - \alpha_4\frac{Kv'\alpha_4'}{\alpha_4} = Kv'(\alpha_1 - \alpha_4')$$

$$(3) \qquad a_2Vfo + a_0 = \alpha_1 Vdes$$

$$(4) \qquad \frac{a_2Vfo}{\alpha_4} \quad \chi_3(0) = \frac{\alpha_1}{\alpha_2}Vdes$$

$$\alpha_4 Kv'Vfo + a_0 = \alpha_1 Vdes$$

$$Kv'Vfo + \chi_3(0) = \frac{\alpha_1}{\alpha_2}Vdes$$

$$a_0 = \alpha_1 V_{des} - \alpha_4 K_v' V_{fo}$$

$$x_3(0) = \frac{\alpha_1}{\alpha_2} V_{des} - K_v' V_{fo}$$

$$\left\{ S(S+\alpha_2)(S+\alpha_4) + \mu K \alpha_0 \alpha_4 K_v' \left[\alpha_1 - \alpha_4' + \alpha_4 \frac{S+\alpha_4'}{\alpha_4} \right] \right\} X_1$$

$$= \mu K \alpha_0 \alpha_4 \left[\alpha_4 K_v' \frac{S+\alpha_4}{\alpha_4} \frac{V_{fo}}{S} + \frac{\alpha_1 V_{des} - \alpha_4 K_v V_{fo}}{S} + \frac{\alpha_1}{\alpha_2} V_{des} - K_v' V_{fo} \right] + S(S+\alpha_2)(S+\alpha_4)\frac{V_f}{S}$$

$$\left[S(S+\alpha_2)(S+\alpha_4') + A(S+\alpha_1) \right] X_1$$

$$= \frac{A}{K_v'} \left[K_v' V_{fo} + K_v' \frac{\alpha_4}{S} V_{fo} - K_v' V_{fo} + \frac{\alpha_1}{\alpha_2}(S+\alpha_2) \frac{V_{des}}{S} \right] + S(S+\alpha_2)(S+\alpha_4)\frac{V_{fo}}{S}$$

$$X_1 = \frac{1}{S} \, \frac{S(S+\alpha_2)(S+\alpha_4) V_{fo} + \frac{A}{K_v'} \frac{\alpha_1}{\alpha_2}(S+\alpha_2) V_{des}}{S(S+\alpha_2)(S+\alpha_4') + A(S+\alpha_1)}$$

$$\frac{dx_1}{dt} = -\alpha_4' x_1 + \alpha_4 x_2 + \alpha_4 V_{fo}, \qquad x_1(0) = V_{fo}$$

$$\frac{dx_2}{dt} = \mu K \alpha_0 x_3, \qquad x_2(0) = 0$$

$$\frac{dx_3}{dt} = K_v'(\alpha_4' - \alpha_1) x_1 - K_v' \alpha_4 x_2 - \alpha_2 x_3 + \alpha_1 - K_v' \alpha_4, \qquad x_3(0) = \frac{\alpha_1}{\alpha_2} - K_v'$$

STEADY STATE SOLUTION $\qquad V_{fo} = V_{des} = 1$

$$0 = -\alpha_4' x_1 + \alpha_4 x_2 + \alpha_4$$

$$0 = \mu K \alpha_0 x_3 \qquad x_3 = 0$$

$$0 = K_v'(\alpha_4' - \alpha_1) x_1 - K_v' \alpha_4 x_2 + \alpha_1 - K_v' \alpha_4$$

$$0 = -K_v' \alpha_4' x_1 + K_v' \alpha_4 x_2 + K_v' \alpha_4$$

STEADY STATE CHECKS

$$-K_v' \alpha_1 x_1 + \alpha_1 = 0$$

$$\chi_1 = \frac{1}{Kv'} \qquad v_{ph} = Kv'\chi_1 = 1$$

$$\chi_2 = \frac{\alpha_4'\chi_1 - \alpha_4}{\alpha_4} = \frac{\alpha_4'}{Kv'\alpha_4} - 1$$

$$V_f = 1 + \chi_2 = \frac{\alpha_4'}{Kv'\alpha_4} = \frac{2.8}{.915 \times 2.35}$$

LAPLACE TRANSFORM CHECK

$$(S+\alpha_4')\chi_1 = \alpha_4\chi_2 + V_{fo} + \frac{\alpha_4 V_{fo}}{S}$$

$$S\chi_2 = \mu K\alpha_0\chi_3$$

$$(S+\alpha_2)\chi_3 = Kv'(\alpha_4' - \alpha_1)\chi_1 - Kv'\alpha_4\chi_2 + \chi_3(0) + \frac{\alpha_1 - Kv'\alpha_4}{S}$$

$$V_{fo} = V_{des} = 1$$

$$S(S+\alpha_2)\chi_2 = \mu K\alpha_0(S+\alpha_2)\chi_3$$

$$S(S+\alpha_2)\alpha_4\chi_2 = \mu K\alpha_0\alpha_4\left[Kv'(\alpha_4' - \alpha_1)\chi_1 - Kv'\alpha_4\chi_2 + \frac{\alpha_1}{\alpha_2} - Kv' + \frac{\alpha_1 - Kv'\alpha_4}{S}\right]$$

$$S(S+\alpha_2)(S+\alpha_4')\chi_1 = S(S+\alpha_2)\alpha_4\chi_2 + S(S+\alpha_2)(S+\alpha_4)\frac{1}{S}$$

$$S(S+\alpha_2)(S+\alpha_4')\chi_1 = A(\alpha_4' - \alpha_1)\chi_1 - A\alpha_4\chi_2 + \frac{A}{Kv'}\frac{\alpha_1}{\alpha_2} - A + \frac{A}{Kv'}\frac{\alpha_1}{S}$$

$$+ S(S+\alpha_2)(S+\alpha_4)\frac{1}{S} - \frac{A\alpha_4}{S}$$

$$\alpha_4\chi_2 = (S+\alpha_4')\chi_1 - \frac{S+\alpha_4}{S}$$

$$S(S+\alpha_2)(S+\alpha_4')\chi_1 = A(\alpha_4' - \alpha_1)\chi_1 - A(S+\alpha_4')\chi_1 + A\frac{S+\alpha_4}{S} + \frac{A}{Kv'}\frac{\alpha_1}{\alpha_2} - A$$

$$+ \frac{A}{Kv'}\frac{\alpha_1}{S} - \frac{A\alpha_4}{S} + S(S+\alpha_2)(S+\alpha_4)\frac{1}{S}$$

$$\left\{S(S+\alpha_2)(S+\alpha_4') + A(S+\alpha_1)\right\}\chi_1 = \frac{A}{Kv'}\frac{\alpha_1}{\alpha_2}\left(\frac{S+\alpha_2}{S}\right) + S(S+\alpha_2)(S+\alpha_4)\frac{1}{S}$$

$$\chi_1 = \frac{1}{S}\;\frac{S(S+\alpha_2)(S+\alpha_4) + \frac{A}{Kv'}\frac{\alpha_1}{\alpha_2}(S+\alpha_2)}{S(S+\alpha_2)(S+\alpha_4') + A(S+\alpha_1)}$$

STEADY STATE

$$0 = -2.8\,X_1 + 2.35\,X_2 + 2.35$$
$$0 = 4797.5\,X_3 \quad X_3 = 0$$
$$0 = -32.025\,X_1 \quad -2.15\,X_2 - 137.2\,X_3 + 35.65$$
$$\underline{0 = -2.562\,X_1 \quad 2.15\,X_2 \qquad\qquad + 2.15}$$
$$0 = -34.587\,X_1 + 37.8$$

$$X_1 = \frac{37.8}{34.587} = 1.0929$$

$$\upsilon_{ph} = 1.0929 \times .915 = 1.$$

COMPUTER RUN

FOR $\quad \alpha_4' = 2.8 \qquad \alpha_0 = 5 = \alpha_3$

$\alpha_4 = 2.35 \qquad \mu K = 959.5$

$K\upsilon' = .915$

$$\alpha_1 = 37.8$$
$$\alpha_2 = 137.2$$

$$\mu K \alpha_0 = 4797.5$$

$$K\upsilon'(\alpha_4' - \alpha_1) = .915(2.8 - 37.8) = -32.025$$

$$K\upsilon' \alpha_4 = .915 \times 2.35 = 2.150$$

$$\alpha_1 - K\upsilon' \alpha_4 = 35.65$$

$$\frac{\alpha_1}{\alpha_2} - K\upsilon' = \frac{37.4}{137.2} - .915 = -.6395$$

$$\frac{dX_1}{dt} = -2.8\,X_1 + 2.35\,X_2 + 2.35$$

$$\frac{dX_2}{dt} = 4797.5\,X_3$$

$$\frac{dX_3}{dt} = -32.025\,X_1 - 2.15\,X_2 - 137.2\,X_3 + 35.65$$

$$\chi_1(0)=1$$
$$\chi_2(0)=0$$
$$\chi_3(0)=-.6345$$

NEW RUN

$$\alpha=50$$
$$\beta=100$$
$$\omega_0^2=7400$$
$$\alpha_2=2\alpha+\beta-\alpha_4'=300-2.8=297.2$$

$$A=\omega_0^2+2\alpha\beta-\alpha_4'\alpha_2=7400+10000-832.16$$
$$A=16567.84$$

$$\alpha_1=\frac{\omega_0^2\beta}{A}=\frac{740000}{16567.84}=44.66$$

$$\mu K\alpha_0=\frac{A}{\alpha_4 K v'}=7705. \qquad \mu K=1541$$

$$Kv'(\alpha_4'-\alpha_1)=38.30$$
$$Kv'\alpha_4=.915\times 2.35=2.15$$

$$\alpha_1-Kv'\alpha_4 \qquad 44.66-2.15=42.51$$

$$\chi_3(0)=\frac{\alpha_1}{\alpha_2}-.915=\frac{44.66}{297.2}-.915=-.7647$$

$$\frac{d\chi_1}{dt}=-2.8\,\chi_1+2.35\,\chi_2+2.35, \qquad \chi_1(0)=1$$

$$\frac{d\chi_2}{dt}=7705\,\chi_3, \qquad \chi_2(0)=0$$

$$\frac{d\chi_3}{dt}=-38.30\chi_1-2.15\chi_2-297.2\chi_3+42.51, \chi_3(0)=-.7647$$

$$\frac{d\chi_3}{dt} = -Kv'(-\alpha_4'\chi_1+\alpha_4\chi_2+\alpha_4)-Kv'\alpha_1\chi_1-\alpha_2\chi_3+\alpha_1$$

$$\frac{d\chi_3}{dt} = -Kv'\frac{d\chi_1}{dt} - \alpha_2(Kv'\chi_1+\chi_3)-Kv'(\alpha_1-\alpha_2)\chi_1+\alpha_1$$

$$\frac{d}{dt} = (\chi_3+Kv'\chi_1)+\alpha_2(\chi_3+Kv'\chi_1)-Kv'(\alpha_1-\alpha_2)\chi_1+\alpha_1$$

$$\frac{d\chi_2}{dt} = \mu K\alpha_0(\chi_3+Kv'\chi_1)-\mu K\alpha_0 Kv'\chi_1$$

$$y_1 = \chi_1$$
$$y_2 = \chi_2$$
$$y_3 = \chi_3+Kv'\chi_1$$

$$\frac{dy_1}{dt} = -\alpha_4' y_1+\alpha_4 y_2+\alpha_4, \qquad y_1=1$$

$$\frac{dy_2}{dt} = \mu K\alpha_0 y_3-\mu K\alpha_0 Kv' y_1, \qquad y_2=0$$

$$\frac{dy_3}{dt} = -\alpha_2 y_3-Kv'(\alpha_1-\alpha_2)y_1+\alpha_1, \qquad y_3=\frac{\alpha_1}{\alpha_2}$$

$$(S+\alpha_4')y_1 = \alpha_4 y_2+\frac{S+\alpha_4}{S}$$

$$Sy_2 = \mu K\alpha_0(y_3-Kv'y_1)$$

$$(S+\alpha_2)y_3 = -Kv'(\alpha_1-\alpha_2)y_1+\frac{\alpha_1}{S}+\frac{\alpha_1}{\alpha_2}$$

$$y_3 = \frac{-Kv'(\alpha_1-\alpha_2)y_1+\frac{\alpha_1}{\alpha_2}\,\frac{S+\alpha_2}{S}}{S+\alpha_2}$$

$$y_2 = \mu K\alpha_0\left[\frac{-Kv'(\alpha_1-\alpha_2)y_1+\frac{\alpha_1}{\alpha_2}}{S+\alpha_2}-Kv'y_1\right]$$

$$y_2 = \mu K\alpha_0\left[\frac{\frac{\alpha_1}{\alpha_2}-Kv'[(\alpha_1-\alpha_2)+S+\alpha_2]y_1}{S(S+\alpha_2)}\right]$$

$$(S+\alpha_4')y_1 = \mu K\alpha_0\alpha_4\left[\frac{\frac{\alpha_1}{\alpha_2} - Kv'(S+\alpha_1)y_1}{S(S+\alpha_2)}\right]$$

$$\left[S(S+\alpha_2)(S+\alpha_4')+A(S+\alpha_1)\right]y_1 = \frac{S(S+\alpha_2)(S+\alpha_4)}{S} + \frac{A}{Kv'}\frac{\alpha_1}{\alpha_2}\frac{(S+\alpha_2)}{S}$$

$$y_1 = \chi_1 = \frac{1}{S}\,\frac{S(S+\alpha_2)(S+\alpha_4)+\frac{A}{Kv'}\frac{\alpha_1}{\alpha_2}(S+\alpha_2)}{S(S+\alpha_2)(S+\alpha_4')+A(S+\alpha_1)}$$

$$\frac{d\chi_1}{dt} = -\alpha_4'\chi_1+\alpha_4\chi_2+\alpha_4 \qquad V_{fo} = V_{des} = 1$$

$$\frac{d^2\chi_1}{dt^2} = -\alpha_4'\frac{d\chi_1}{dt}+\alpha_4\frac{d\chi_2}{dt}$$

$$= -\alpha_4'(-\alpha_4'\chi_1+\alpha_4\chi_2+\alpha_4)+\alpha_4\mu K\alpha_0\chi_3$$

$$\frac{d^3\chi_1}{dt^3} = \alpha_4'^2\frac{d\chi_1}{dt} - \alpha_4\alpha_4'\frac{d\chi_2}{dt} + \mu K\alpha_0\alpha_4\frac{d\chi_3}{dt}$$

$$\frac{d\chi_3}{dt} = -Kv'(-\alpha_4'\chi_1+\alpha_4\chi_2+\alpha_4) - Kv'\alpha_1\chi_1+\alpha_1$$

$$\frac{d\chi_3}{dt} = -Kv'\frac{d\chi_1}{dt} - \alpha_1(Kv'\chi_1-1) - \alpha_2\chi_3$$

$$\alpha_4\frac{d^2\chi_2}{dt^2} = \mu K\alpha_0\alpha_4\left[-Kv'\frac{d\chi_1}{dt} - \alpha_1(Kv'\chi_1-1) - \alpha_2\chi_3\right]$$

$$\frac{d^3\chi_1}{dt} = -\alpha_4'\frac{d^2\chi_1}{dt^2} + \alpha_4\frac{d^2\chi_2}{dt^2}$$

$$\alpha_4\chi_3 = \frac{\alpha_4}{\mu K\alpha_0}\frac{d\chi_2}{dt}$$

$$\alpha_4\chi_3 = \frac{1}{\mu K\alpha_0}\left(\alpha_4'\frac{d\chi_1}{dt} + \frac{d^2\chi_1}{dt^2}\right)$$

$$\frac{d^3\chi_1}{dt^3} = -\alpha_4'\frac{d^2\chi_1}{dt^2} + \mu K\alpha_0\alpha_4 Kv'\left[-\frac{d\chi_1}{dt} - \alpha_1\chi_1\right] + \mu K\alpha_0\alpha_4\alpha_1 - \alpha_2\alpha_4'\frac{d\chi_1}{dt} - \alpha_2\frac{d^2\chi_1}{dt^2}$$

$$\frac{d^3\chi_1}{dt} + (\alpha_4'+\alpha_2)\frac{d^2\chi_1}{dt^2} + (A+\alpha_2\alpha_4')\frac{d\chi_1}{dt} + A\alpha_1\chi_1 - \frac{A}{Kv'}\alpha_1 = 0$$

$$S^3\chi_1 - S^2\chi_1(0) - S\dot{\chi}_1(0) - \ddot{\chi}_1(0) + (\alpha_4' + \alpha_2)(S^2\chi_1 - S\chi_1(0) - \chi_1(0))$$

$$(\alpha_2\alpha_4' + A)(S\chi_1 - \chi_1(0)) + A\alpha_1\chi_1 - \frac{A}{Kv'}\frac{\alpha_1}{S}$$

$$\frac{d^3\chi_1}{dt^2} + (\alpha_4' + \alpha_2)\frac{d^2\chi_1}{dt^2} + (A + \alpha_2\alpha_4)'\frac{d\chi_1}{dt} + A\alpha_1\chi_1 - \frac{A}{Kv'}\alpha_1 = 0$$

$$(\alpha_4' + \alpha_2) = 2\alpha + \beta, \quad (A + \alpha_2\alpha_4') = 2\alpha\beta + \omega_0^2, \quad A\alpha_1 = \omega_0^2\beta$$

$$\chi_1(0) = 1$$
$$\dot{\chi}_1(0) = \alpha_4 - \alpha_4'$$
$$\ddot{\chi}(0) = -\alpha_4'(\alpha_4 - \alpha_4') + \frac{A}{Kv'}\frac{\alpha_1}{\alpha_2} - A$$

$$\frac{d^3\chi_1}{dt^2} + (2\alpha + \beta)\frac{d^2\chi_1}{dt^2} + (2\alpha\beta + \omega_0^2)\frac{d\chi_1}{dt} + \omega_0^2\beta\chi_1 = \frac{\omega_0^2\beta}{Kv'}$$

$$y_1 = \chi_1$$
$$y_2 = \frac{d\chi_1}{dt} = \frac{dy_1}{dt}$$
$$y_3 = \frac{d^2\chi_1}{dt^2} = \frac{dy_2}{dt}$$

$$\frac{dy_1}{dt} = y_2$$

$$\frac{dy_2}{dt} = y_3$$

$$\frac{dy_3}{dt} = -\omega_0^2\beta y_1 - (2\alpha\beta + \omega_0^2)y_2 - (2\alpha + \beta)y_3 + \frac{\omega_0^2\beta}{Kv'}$$

$$-\omega_0^2\beta y_1 + \frac{\omega_0^2\beta}{Kv'} = 0$$

$$y_1(0) = 1$$
$$y_2(0) = \alpha_4 - \alpha_4'$$
$$y_3(0) = \alpha_4'(\alpha_4 - \alpha_4') + A\left(\frac{\alpha_1}{Kv'\alpha_2} - 1\right)$$

$$\left[S^3 + (\alpha_4' + \alpha_2)S^2 + (A + \alpha_2\alpha_4')S + A\alpha_1\right]\chi_1 = \left[S^2 + (\alpha_2 + \alpha_4')S + (\alpha_2\alpha_4' + A)\right]\chi_1(0)$$
$$+ \left[S + (\alpha_2 + \alpha_4')\right]\dot{\chi}_1(0) + \ddot{\chi}_1(0)$$

$$x_1(0)=1$$

$$\dot{x}_1(0)=-\alpha_4'+\alpha_4 \qquad x_2(0)=0$$

$$\ddot{x}_1(0)=-\alpha_4'\dot{x}_1(0)+\alpha_4\mu K\alpha_0\,x_3(0)$$

$$\dddot{x}_1(0)=\alpha_4'^2-\alpha_4'\alpha_4+\alpha_4\mu K\alpha_0\left(\frac{\alpha_1}{\alpha_2}-Kv'\right)$$

$$S\alpha_4-S\alpha_4'+\alpha_2\alpha_4-\alpha_2\alpha_4'+\alpha_4'\alpha_4-\alpha_4'^2$$

$$x_1=\frac{\left[S^2+(\alpha_2+\alpha_4')S+\alpha_2\alpha_4'+A\right]+(S+\alpha_2+\alpha_4')(\alpha_4-\alpha_4')+\alpha_4'^2-\alpha_4'\alpha_4+\frac{A}{Kv'}\frac{\alpha_1}{\alpha_2}-A}{S(S+\alpha_4')(S+\alpha_2)+A(S+\alpha_1)}$$

$$x_1=\frac{S^2+(\alpha_2+\alpha_4)S+\alpha_2\alpha_4+\frac{A}{Kv'}\frac{\alpha_1}{\alpha_2}\frac{\alpha_1}{S}}{S(S+\alpha_4')(S+\alpha_2)+A(S+\alpha_1)}$$

$$x_1=\frac{1}{S}\,\frac{S(S+\alpha_2)(S+\alpha_4)+\frac{A}{Kv'}\frac{\alpha_1}{\alpha_2}(S+\alpha_2)}{S(S+\alpha_2)(S+\alpha_4')+A(S+\alpha_1)}$$

WHICH CHECKS

$$S^2+2\alpha S+\alpha^2+W_0^2-\alpha^2W_0^2=\alpha^2+W_1^2$$

$$y_1=\frac{1}{Kv'}+ae^{-\beta t}+e^{-\alpha t}\left[B\cos W_1t+C\sin W_1t\right]$$

$$y_2=-a\beta e^{-\beta t}+e^{-\alpha t}\left[-W_1B\sin W_1t+W_1C\cos W_1t-\alpha B\cos W_1t-\alpha C\sin W_1t\right]$$

$$y_2=-a\beta e^{-\beta t}-e^{-\alpha t}\left[(\alpha B-W_1C)\cos W_1t+(\alpha C+W_1B)\sin W_1t\right]$$

$$y_3=a\beta^2e^{-\beta t}-e^{-\alpha t}\left[(\alpha B-W_1C)(-W_1)\sin W_1t+(\alpha C+W_1B)W_1\cos W_1t+(\alpha B-W_1C)(-\alpha)\cos W_1t+(\alpha C+W_1B)(-\alpha)\sin W_1t\right]$$

$$y_3=a\beta^2e^{-\beta t}-e^{-\alpha t}\left[(-\alpha W_1B+W_1^2C-\alpha^2C-\alpha W_1B)\sin W_1t\,(\alpha CW_1+W_1^2B-\alpha^2B+\alpha W_1C)\cos W_1t\right]$$

$$y_3 = a\beta^2\epsilon^{-\beta t} - C^{-\alpha t}\left[\left\{(\omega_1^2-\alpha^2)C - 2\alpha\omega_1 B\right\}\sin\omega_1 t\left\{(\omega_1^2-\alpha^2)B + 2\alpha\omega_1 C\right\}\cos\omega_1 t\right]$$

$$y_1(0) = \frac{1}{Kv'} + a + B - \frac{1}{Kv'} + 1 - \frac{1}{Kv'} = 1$$

$$y_2(0) = -a\beta - \alpha B + \omega_1 C = \alpha_4 - \alpha_4'$$

$$y_3(0) = a\beta^2 - (\omega_1^2-\alpha^2)B - 2\alpha\omega_1 C = \alpha_4'(\alpha_4-\alpha_4') + \frac{A}{Kv'}\,\frac{\alpha_1 - Kv'\alpha_2}{\alpha_2}$$

$$a + B = 1 - \frac{1}{Kv'}$$

$$a\beta + \alpha B - \omega_1 C = \alpha_4' - \alpha_4$$

$$a\beta^2 - (\omega_1^2-\alpha^2)B - 2\alpha\omega_1 C = \alpha_4'(\alpha_4-\alpha_4') + \frac{A}{Kv'}\left(\frac{\alpha_1}{\alpha_2} - Kv'\right)$$

$$2\alpha\beta a + 2\alpha^2 B - 2\alpha\omega_1 \epsilon = -2\alpha(\alpha_4-\alpha_4')$$

$$a(\beta^2 - 2\alpha\beta) - B(\omega_0^2) = (\alpha_4' + 2\alpha)(\alpha_4-\alpha_4') + \frac{A}{Kv'}\left(\frac{\alpha_1}{\alpha_2} - Kv'\right)$$

$$a(\beta^2 - 2\alpha\beta + \omega_0^2) - \left(1 - \frac{1}{Kv'}\right)\omega_0^2 = (\alpha_4' + 2\alpha)(\alpha_4-\alpha_4') + \frac{A}{Kv'}\left(\frac{\alpha_1}{\alpha_2} - Kv'\right)$$

$$a = \frac{\left(1-\frac{1}{Kv'}\right)\omega_0^2 - (\alpha_4'+2\alpha)(\alpha_4'-\alpha_4) + \frac{A}{Kv'}\left(\frac{\alpha_1}{\alpha_2} - Kv'\right)}{\beta^2 - 2\alpha\beta + \omega_0^2}$$

$$\chi_1(0) = 1$$
$$\chi_2(0) = 0$$

$$y_1 = \chi_1$$

$$y_2 = \frac{d\chi_1}{dt} = -\alpha_4'\chi_1 + \alpha_4\chi_2 + \alpha_4$$

$$y_2(0) = \alpha_4 - \alpha_4'$$

$$y_3 = \frac{d^2\chi_1}{dt^2} = \frac{dy_2}{dt} = -\alpha_4'(-\alpha_4'\chi_1 + \alpha_4\chi_2 + \alpha_4) + \frac{A}{Kv'}\chi_3$$

$$y_3(0) = +\alpha_4'(\alpha_4' - \alpha_4) + \frac{A}{Kv'}\left(\frac{\alpha_1}{\alpha_2} - Kv'\right) = \alpha_4'\left(\frac{\alpha_4'}{Kv'} - \alpha_4\right) + \frac{A}{Kv'}\left(\frac{\alpha_1}{\alpha_2} - 1\right) - \frac{\alpha_4'^2}{Kv'} + \alpha_4'^2 - \frac{A}{Kv'}\left(1 - \frac{1}{Kv'}\right)$$

$$y_3(0) = \left(1 - \frac{1}{Kv'}\right)(\alpha_4'^2) + \frac{A}{Kv'}\,\frac{\alpha_1 - \alpha_2}{\alpha_2} + \alpha_4'\left(\frac{\alpha_4'}{Kv'} - \alpha_4\right)$$

$$y_2(0) = \alpha_4 - \frac{\alpha_4'}{Kv'} - \alpha_4'\left(1 - \frac{1}{Kv'}\right)$$

$$P = 1 - \frac{1}{Kv'} \qquad Q = \alpha_4 - \frac{\alpha_4}{Kv'} \qquad R = \frac{A}{Kv'}\,\frac{\alpha_1 - \alpha_2}{\alpha_2}$$

$$a = \frac{(\beta - \alpha_2)[\beta P - Q] + R}{\beta^2 - 2\alpha\beta + \omega_0^2}$$

$$B = P - a$$

$$C\omega_1 = \frac{[\alpha_2(\omega_0^2 - \alpha\beta) + 2\alpha^2\beta - (\alpha+\beta)\omega_0^2]P + [\omega_0^2 - \alpha\beta + \alpha_2(\beta - \alpha)]Q + (\beta - \alpha)R}{\beta^2 - 2\alpha\beta + \omega_0^2}$$

$$\omega_0^2 - \alpha_2^2 = \omega_1^2$$

$$a + B = P$$
$$-a\beta - \alpha B + \omega_1 C = Q - \alpha_4' P$$
$$a\beta^2 - (\omega_1^2 - \alpha^2)B - 2\alpha\omega_1 C = P(\alpha_4'^2 - A) + R - \alpha_4' Q$$
$$-2\alpha\beta a - 2\alpha^2 B + 2\alpha\omega_1 C = -P(2\alpha\alpha_4') + 2\alpha Q$$

$$(\beta^2 - 2\alpha\beta)a - (\omega_1^2 - \alpha^2 + 2\alpha^2)B = (\alpha_4'^2 - A - 2\alpha\alpha_4')P + R + Q(2\alpha - \alpha_4')$$

$$(\beta^2 - 2\alpha\beta)a - \omega_0^2(P - a) = [\alpha_4'(\beta - \alpha_2) - A]P + R - Q(\beta - \alpha_2)$$

$$a = \frac{[\alpha_4'(\beta - \alpha_2) - A + \omega_0^2]P + R - (\beta - \alpha_2)Q}{\beta^2 - 2\alpha\beta + \omega_0^2}$$

$$a = \frac{[\beta\alpha_4' - \omega_0^2 - 2\alpha\beta + \omega_0^2]P + R - (\beta - \alpha_2)Q}{\beta^2 - 2\alpha\beta + \omega_0^2}$$

$$a = \frac{(\beta - \alpha_2)[\beta P - Q] + R}{\beta^2 - 2\alpha\beta + \omega_0^2}$$

$$B=P-A$$

$$
\begin{aligned}
W_1C &= Q-\alpha_4'P+\alpha B+\beta a \\
&= Q-\alpha_4'P+\alpha(P-a)+\beta a \\
&= Q+(\alpha-\alpha_4')P+(\beta-\alpha)a \\
&= Q+(\alpha-\alpha_4')P+\frac{(\beta-\alpha)(\beta-\alpha_2)[\beta P-Q]+(\beta-\alpha)R}{\beta^2-2\alpha\beta+W_o^2} \\
&= \frac{Q[\beta^2-2\alpha\beta+W_o^2-\beta^2+\beta(\alpha+\alpha_2)-\alpha\alpha_2]-P[(\alpha+\beta-\alpha_2)(\beta^2-2\alpha\beta+W_o^2)-\beta^2+\beta^2(\alpha+\alpha_2)-\alpha_2\beta]+(\beta-\alpha)R}{\beta^2-2\alpha\beta+W_o^2}
\end{aligned}
$$

$$W_1C=\frac{Q[W_o^2-\alpha\beta+\alpha_2(\beta-\alpha)]-P[(\alpha+\beta)W_o^2-2\alpha^2\beta-\alpha_2(W_o^2-\alpha\beta)]+(\beta-\alpha)R}{\beta^2-2\alpha\beta+W_o^2}$$

$$10000-10000+7400=7400$$

$$
\begin{array}{c}
2\alpha+\beta \\
\underline{\beta-\alpha} \\
\underline{2\alpha\beta+\beta^2-2\alpha^2-\alpha\beta} \\
\beta^2-2\alpha^2+\alpha\beta
\end{array}
$$

$$a=\frac{(\beta-\alpha)\ \beta P-Q\ +R}{\beta^2-2\alpha^2+W_o^2}$$

$$B=P-a$$

$$W_1C=\frac{Q[W_o^2+\beta^2-2\alpha^2-\alpha_4'(\beta+\alpha)]-P[\alpha(\beta^2-W_o^2)+\alpha_4'(W_o^2-\alpha\beta)]+(\beta-\alpha)R}{\beta^2-2\alpha\beta+W_o^2}$$

SEE REFERENCES (g), (i), (j), and (m)

The maximum and minimum limits of the voltage surge, as described by MIL-STD-704C can be seen on Figure 5 of this report.

The regulator that is to be used in conjunction with the generator, must be within these limits.

Figures 8, 9, and 10 show graphically the various designs that were investigated.

APPENDIX D

DETAILED GENERATOR TEST RESULTS

LIST OF EQUIPMENT

QUANTITY	DESCRIPTION
1	Resistive Load Bank - 0 - 325 KW
1	Inductance Load Bank Unit - .75 pF
1	3 phase Circuit Breaker - 125 amps
3	Current Transformer 40:1, Weston Model 461, Freq. 25 -400 HZ Line Volt 2500
3	AC Ammeter, Weston Model, 0 - 1 - 5 - 10 amps, 85 - 500 HZ
1	D.C. Ampmeter, Weston Model, 0 - 3 - 15 - 30 amps
1	Voltmeter A.C., Weston Model, 0 - 150 - 300 - 600 volts Freq. 25 - 1000 HZ
2	Wattmeter, Weston Model, 0 - 350 - 700 - 1400 watts Max volts - 400, Max amp - 7.5, Rated amp - 5
1	Frequency Counter, Hewlett Packard Model 5226C
1	Viscorder Oscillograph, Model 906C
1	Spectrum Analyzer, Hewlett Packard Model 3580A
1	Digital Multimeter, Data Precision Model 3500
1	Oscilloscope, Tektronix Model 7704A
1	Voltmeter D. C., Weston Model, 0 - 7.5 - 30 - 75 volts
1	Signal Generator, Wavetek Model 111B

TEST DATA

Input Data Engine: White Diesel, 90 Horsepower, 6 Cylinder

Generator: Electric Machine, 30 KW, Freq. 400 HZ
3 phase, 120/200 volts

Test Requirement: Military Standard 704B

Test Method: Military Standard 705B
Military Handbook 705B

SECTION	REQUIREMENT
5.1	AC Power Characteristics:

Line to neutral or ground 115/200 volts
Nominal frequency of 400 HZ. Alternate standard - line to neutral or ground 230/400 volts.

(1) Test Method: Mil-Std-705B, Section 608
Mil-Handbook 705, Method 205.1

(2) Results: (a) Line to neutral voltage 113 volts
(b) Nominal frequency 400 HZ

5.1.1.1 AC Voltage Magnitude:

Steady-state voltage 108.0 to 118.0 volts. In emergency mode 102.0 to 124.0 volts.

(1) Test Method: Mil-Std-705B, Section 608
Mil-Handbook 705, Methods 101.1, 205.1

(2) Result: (a) Steady state voltage 113 volts

5.1.1.2 Voltage Unbalance shall be less than three volts.

(1) Test Method: Mil-Std-705, Section 620
Mil-Handbook 705, Section 205

(2) Results: As follows:

UNBALANCE TESTS

1-24-77

	Unity P.F. I = 4094	Full Load 150 V scale
Van =	115.0	117.4
Vbn =	116.0	117.4
Vcn =	115.0	117.4

Ia = 2.10
Ib = 2.10
Ic = 2.10

Van =	113.5	111.5
Vbn =	117.0	115
Vcn =	117.0	

Ia = 2.04
Ib = .668
Ic = .662

P_1 = 380 P_2 = 375

Ic = 2.07
Ib = 2.12
Ia = 2.18

$\frac{6.27}{3} = 2.09$

3 x 2.09 x 40

I = 4094, 300 V scale	Digital Probe to N	Digital Probe to Line
Van = 117	117.1	119.7
Vbn = 118	123.8	117.8
Vcn = 117	120.6	118.3

I = 4094, 150V scale

	Unity P.F.	Digital Probe to Line
Van =	118.3	119.3
Vbn =	119.0	117.8
Vcn =	118.5	118.3

UNBALANCE TESTS

1-24-77 P.M.

I = 4094

Time 2:20	Van = 114.5		Freq. 400 HZ	
	Vbn = 114.0			
	Vcn = 114.0			
Time 2:30	NO LOAD			
	Van = 114.3			
	Vbn = 114.8			
	Vcn = 114.5			
Time 2:35	LOAD o P.F.			
	Van = 115.0	Ia = 2.55		
	Vbn = 115.8	Ib = 2.55		
	Vcn = 115.0	Ic = 2.54		
Time 2:40	BALANCED LOAD			
	Van = 115	Ia = 2.18		P_1 = 378
	Vbn = 115.8	Ib = 2.18		
	Vcn = 115	Ic = 2.18		P_2
Time 2:47	BALANCED LOAD			
	Van = 114.6	Ia = 2.18		P_1 = 378
	Vbn = 115.5	Ib = 2.17		
	Vcn = 114.7	Ic = 2.17		P_2 = 376
Time 2:56	UNBALANCE			
	Van = 111.2	Ia = 2.12		
	Vbn = 114.6	Ib = .743		
	Vcn = 114.6	Ic = .743		
Time 3:05	Van = 111.2	Ia = 2.12		
	Vbn = 114.6	Ib = .670		
	Vcn = 114.6	Ic = .670		

UNBALANCE TESTS

BALANCED .8 P.F. LOAD

Vab = 200.0
Vbc = 200.5
Vac = 199.5

Van = 117.7
Vbn = 116.6
Vcn = 117.3

Ib = 2.15
Ia = Ic = .7166

Van = 113.0	Ia = 2.16	
Vbn = 116.1	Ib = .675	.72
Vcn = 116.1	Ic = .675	.72

Van = 113.0	Ia = 2.6
Vbn = 116.2	Ib = .75
Vcn = 116.3	Ic = .75

Vab = 199 200.5
Vac = 198 200 $\frac{602}{3} = 200.66$
Vbc = 199.5 201.5

Ia = 2.75
Ib = 2.74 $\frac{8.23}{3} = 2.743$
Ic = 2.74

P = VI 1.732 x 2.743 x 200.66 x 40 = 39

$P_1 = 200$
$P_2 = \frac{555}{755} \times 40 = 30.1$

Vab = 199.5
Vac = 198.5
Vbc = 200.5

$$\frac{598.5}{3} = 199.5$$

Ia = 2.75
Ib = 2.73 2.733
Ic = 2.72

3 2.733 x 199.5 x 40 = 38

P_1 = 210
P_2 = 540
750 x 40 = 30

P.F. = .779

$$\frac{3 \times 120 \times 4.34K}{1000} \quad \frac{1.530K}{1000}$$ 3.15 KW

1/3 1/6 1/3 2/3

2/3 1/6 1/3

	1	2	3
Van	112.6	112.8	113
Vbn	116.2	116.2	116.2
Vcn	116.2	116.2	116.2

UNBALANCE RECHECK PURE RESISTANCE LOAD

1-31-77 Voltimeter I = 4094 Freq. 400

Van = 117.0
Vbn = 120.2 3.4
Vcn = 120.4

Ia 2.15 x 40 = 86 amps
Ib .707 x 40 = 28.3
Ic .698 x 40 = 27.9

8:30 A.M.

$P_1 = 2.90$ $\quad P_2 = 1.20 \quad P = 4.10 \times 40 = 16.400$ watts

$\begin{array}{r} 1.20 \\ \hline 4.10 \end{array}$

$\frac{16.400}{30000} = .546$

No change in voltage or frequency settings.

Van = 117.6   Ia = 2.15 x 4
Vbn = 121.0   3.4   Ib = .707   8:55 A.M.
Vcn = 121.0   Ic = .698

Vab = 198
Vbc = 202   9:00 A.M.
Vca = 203

Van = 118.4
Vbn = 121.8   3.4   9:15 A.M.
Vcn = 121.8

With coil of 1-0 wire as added

Van = 117.6   Measured on
Vbn = 121.5   general side of   9:45 A.M.
Vcn = 122.2   added impedance

Van = 117.8   Ian = 2.14 x 40
Vbn = 121.8   Ibn = .73 x 40   10:15 A.M.
Vcn = 122.0   Icn = .688 x 40

Van = 119
Vbn = 122.5   10:45 A.M.
Vcn = 122.5

Van rose from 117.0 at 8:30 to 119 at 10:45
without any change in voltage setting.

Readjusted voltages to (at no load)

Van = 118.0   Note that with things
Vbn = 118.0   well warmed up no load   10:55 A.M.
Vcn = 116.7   voltages are balanced.

With neutral impedance wire unwound on floor.

Van = 113.0   Ian = 2.13 x 40
Vbn = 116.7   3.7   Ibn = .655 x 40   11:00 A.M.
Vcn = 116.7   Icn = .655 x 40

Load was a little high, so readjusted load bank.

Van = 114.0   Ian = 1.85
Vbn = 117.0   Ibn = .600   11:20 A.M.
Vcu = 117.0   I   Icn = .600

$P_1 = 315 \quad P_2 = 100 \quad 415 \times 40 \quad \frac{.16600}{30000} = .553$

No load

Van = 118.3
Vbn = 118.3 11:40 A.M.
Vcn = 118.3

1-31-77 After shut down for lunch.

No load.

Van = 118.0
Vbn = 118.0 1:40 P.M.
Vcn = 118.0

Full Load on Phase A 1/3 load on Phases B & C
I = 4094 Digital

Van = 114.5		113.6	Ian	
Vbn = 117.2	Batteries	114.3	Ibn	1:50 P.M.
Vcn = 117.2	Low	115.1	Icn	

$P_1 = 290 \quad P_2 = 100 \quad P = 390 \times 40 = \frac{15600}{30000} = .520$

Van = 115 Ian = 1.578
Vbn = 117.7 Ibn = .590
Vcn = 117.8 Icn = .585

$P_1 = 295 \quad P_2 = 95 \quad P = 390 \times 40 = \frac{15600}{30000} = .553$

Added 1 switch to each phase. Freq. 400 HZ

$P_1 = 305 \quad P_2 = 110 \quad P = 415 \times 40 = \frac{16600}{30000} = .553$

Van = 115 Ian = 1.85 x 40
Vbn = 118 Ibn = .587 x 40
Vcn = 118 Icn = .587 x 40

2-7-77

Check for Unit P.F. balanced rated load. Freq. 400 HZ

Digital I = 4094

114.15	Van	115.2	Ia = 2.18 x 40		
113.25	Vbn	116.2	Ib = 2.12 x 40	Iav	= 2.16
114.00	Vcn	115.0	Ic = 2.18 x 40	Vav	= 115.5

$P_1 = 375 \quad P_2 = 382$ 9:30 A.M.

$$\begin{array}{r} 375 \\ \underline{382} \\ 757 \times 40 = 30100 \end{array}$$

$3 \times 115 \times Ia = 30000$

$Ia = 2.18$

$3 \times 115.5 \times 2.16 \times 40 = 30000$

V across R_7 and R_{13} V across R_{15}

Simpson

10.2 volts	9:45	
10.2 volts	9:50	23.8
10.2 volts	10:15	

Digital $I = 4094$

113.7	Van = 115.0	Ia = 2.18 x 40	Iav = 213.5
113.2	Vbn = 116.4	Ib = 2.10 x 40	Vav = 115.5
114.0	Vcn = 115.0	Ic = 2.18 x 40	

$P_1 = 365$ $P_2 = 375$

$\underline{375}$

$740 \times 40 = 29,600$ 10:10 A.M.

$40 \times 3 \times 115.5 \times 213.5 = 29400$

With new meters but old CT's

Van = 114.4	Ia = 2.17	Vav = 111.86
Vbn = 112.2	Ib = 2.10	Iav = 2.186
Vcn = 111.0	Ic = 2.19	

$P_1 = 369$ $P_2 = 381$

$\underline{381}$

$745 \times 40 = 29800$ watts

$3 \times 111.86 \times 2.186 \times 40 = 31200$

Rebalance load - raised voltage

Van = 114.9	Ia = 2.24	Iav = 2.25
Vbn = 115.8	Ib = 2.24	Vav = 115.1
Vcn = 114.6	Ic = 2.27	

$P_1 = 380$ $P_2 = 403$

$\underline{403}$

$783 \times 40 = 31200$

$3 \times 115.1 \times 2.25 \times 40 = 31200$

No Load

Van = 115.9
Vbn = 116.0
Vcn = 116.0

Van = 114.8	Ia = 2.15	
Vbn = 115.6	Ib = 2.16	Iav = 2.17
Vcn = 114.5	Ic = 2.20	Vav = 114.9

$P_1 = 362 \quad P_2 = 395$

$$\begin{array}{r} 362 \\ \underline{395} \\ 757 \end{array} \times 40 = 30{,}280$$

$3 \times 114.9 \times 2.17 \times 40 = 29{,}800$

SECTION REQUIREMENT

5.1.1.3 Voltage Phase Difference shall be within 120° ± 2°

(1) Test Method: Mil-Std-705, Section 507.1e and
Section 508.1e
Mil-Handbook 705, Section 116.1

(2) Results: As follows:

VOLTAGE PHASE DIFFERENCE TEST

3-7-77

No Load

An = 115.0	AB = 198.8
Bn = 115.2	AC = 200.6
Cn = 115.1	BC = 199.0

$\cos \Theta_{AB} = -.496 \qquad \cos \Theta_{BC} = .498 \qquad \cos \Theta_{AC} = -.525$

$\Theta_{AB} = 119.73 \qquad \Theta_{BC} = 119.85 \qquad \Theta_{AC} = 121.64$

No Load

BC = 199.45	An = 115.1
AB = 200.35	Bn = 115.3
AC = 200.35	Cn = 115.2

$\cos \Theta_{AB} = -.517 \qquad \cos \Theta_{AC} = -.518 \qquad \cos \Theta_{BC} = -.463$

$\Theta_{AB} = 121.118 \qquad \Theta_{AC} = 121.207 \qquad \Theta_{BC} = 117.565$

Load - 1/3 load on Phase C, Full load on Phases A and B

ia = 2.1 P_1 = 157.6
ib = 2.1
ic = .717 P_2 = 62
iAV = 1.64

V_{AN} = 113.1 V_{AB} = 197.95
V_{BN} = 112.85 V_{BC} = 196.5
V_{CN} = 115.6 V_{AC} = 200.0
V_{AV} = 113.45 V_{AV} = 197.55

Cos Θ_{AB} = -.52 Cos Θ_{BC} = -.48 Cos Θ_{AC} = .53
Θ_{AB} = 121.3 Θ_{BC} = 118.66 Θ_{AC} = 121.97

3-7-77 3:00 P.M. Load - 1/3 Load Phase C, Full load Phases A and B

ia = 2.08 P_1 = 175
ib = 2.08
ic = .715 P_2 = 62

Van = 113.01 V_{AB} = 195.17 - 195.64 (195.405)
Vbn = 113.05 195.73 - 196.23 (195.98)
Vcn = 115.82 V_{AB} AVERAGE = 195.693
Vav = 113.96

V_{AC} = 200.58 - 201.1 (200.84)
199.96 - 200.38 (200.17)
V_{AC} AVERAGE = 200.505

V_{BC} = 194.42 - 194.96 (194.69)
194.99 - 195.49 (195.24)
V_{BC} AVERAGE = 194.965

Cos Θ_{AB} = -.499 Cos Θ_{BC} = -.451 Cos Θ_{AC} = -.535
Θ_{AB} = 119.9 Θ_{BC} = 116.824 Θ_{AC} = 122.374

3:30 P.M.

Load - 1/3 load Phase C, full load Phases A and B.

V_{AN} - 1.061 V_{AB} - 1.8347 - 1.8441 (1.839)
V_{BN} - 1.064 V_{BC} - 1.823 - 1.8268 (1.825)
V_{CN} - 1.0834 V_{AC} - 1.8714 - 1.8825 (1.877)

Cos Θ_{AB} = -.498 Cos Θ_{BC} = -.444 Cos Θ_{AC} = -.532

Θ_{AB} = 119.859 Θ_{BC} = 116.391 Θ_{AC} = 122.158

3-8-77
No Load

Time interval between phases: AB - 832 microseconds
BC - 835 microseconds
AC - 830 microseconds

Conversion of microseconds to degrees: $\frac{X}{833.33}$ .120 = degrees

AB - 832 microseconds $\frac{832}{833.33}$ .120 = 119.8°

BC - 835 microseconds $\frac{835}{833.33}$ .120 = 120.2°

AC - 830 microseconds $\frac{830}{833.33}$ .120 = 119.5°

all within specifications

LOAD - 1/3 load Phase C, full load Phases A and B

Time interval between phases: AB - 834 microseconds
BC - 815 microseconds
AC - 851 microseconds

Conversion of microseconds to degrees: $\frac{X}{833.33}$ .120 = degrees

AB - 834 microseconds $\frac{834}{833.33}$ .120 = 120.1°

BC - 815 microseconds $\frac{815}{833.33}$ .120 = 117.4°

AC - 851 microseconds $\frac{851}{833.33}$ .120 = 122.5°

3-14-77 PHASE ANGLE TEST

No Load - set voltages

Van = 115.0
Vbn = 115.2
Vcn = 115.2

Load - Phase A, full load
B, 1/3 full
C, 1/3 full

V_{AB} = 188.0 Ia = 2.08 x 40
V_{BC} = 200.2 Ib = .663 x 40
V_{AC} = 200.3 Ic = .642 x 40

Phases	Time Interval	Degrees
AB	811 microseconds	116.8°
BC	835 microseconds	120.2°
AC	855 microseconds	123.1°

No Load Check

Phases	Time Interval	Degrees
AB	833 microseconds	120°
BC	834 microseconds	120.1°
AC	837 microseconds	120.5°

3-14-77 - 12:30 P.M.

Full load, Phase A - 1/3 load, Phases B and C

$P_1 = 155$ $P_2 = 53$ Total Power = $(P_1 + P_2)$ 80

Total Power = 16640 good

ia = 1.85 x 40 $V_{AB} = 190$
ib = .59 x 40 $V_{AC} = 200.4$
ic = .602 x 40 $V_{BC} = 200.3$

Phases	Time Interval	Degrees
AB	819 microseconds	117.9°
BC	837 microseconds	120.5°
AC	852 microseconds	122.7°

Full load, Phase B - 1/3 load, Phases A and C

Van = 118.2 ia = .678 x 40
Vbn = 117.8 ib = 1.85 x 40
Vcn = 118.0 ic = .690 x 40

Phases	Time Interval	Degrees
AB	853 microseconds	122.8°
BC	832 microseconds	119.8°
AC	822 microseconds	118.4°

Full load, Phase C - 1/3 load, Phases A and B

Van = 119.0 ia = .694 x 40
Vbn = 120.5 ib = .682 x 40
Vcn = 115.9 ic = 2.03 x 40

Phases	Time Interval	Degrees
AB	830 microseconds	119.5°
BC	859 microseconds	123.7°
AC	813 microseconds	117.1°

Impedence put in neutral:

Phases	Time Interval	Degrees
AB	830 microseconds	119.5°
BC	842 microseconds	121.2°
AC	811 microseconds	116.8°
AB	839 microseconds	120.8°
BC	862 microseconds	124.1°
AC	816 microseconds	117.5°

3-14-77 3:30 P.M. Full load on Phase C - 1/3 load on Phases A and B

Period - 2500 microseconds

With Neutral react.

Phases	Time Interval	Degrees
AB	829 microseconds	119.4°
BC	857 microseconds	123.4°
AC	810 microseconds	116.6°

Without Neutral react.

AB	828 microseconds	119.2°
BC	855 microseconds	123.1°
AC	810 microseconds	116.6°

3-28-77 Phase Angle Test using digital voltmeter and a 4 to 1 potential transformer.

Balanced

Vac = 5.07 ia = 2.2
Vab = 50.7 ib = 2.2
Vbc = 50.8 ic = 2.3

Van = 29.3
Vbn = 29.3
Vcn = 29.35

$$\cos \theta_{AB} = - \frac{V_{AB}^2 - V_{AN}^2 - V_{BN}^2}{2VanVbn}$$

θ_{AB} = 119.8
θ_{BC} = 120.02
θ_{AC} = 119.6 all within specifications

Unbalanced Load

Vab = 51.65	Van = 29.6	ia = .694
Vbc = 52.15	Vbn = 30.15	ib = .693
Vac = 50.3	Vcn = 29.25	ic = 2.2

Cos θ_{AB} = -.494 θ_{AB} = 119.6

Cos θ_{BC} = -.541 θ_{BC} = 122.8

Cos θ_{AC} = -.461 θ_{AC} = 117.5 not in specifications

Second trial using different voltmeter:

Vab = 51.067	ia = .693	Van = 29.339
Vbc = 51.509	ib = .693	Vbn = 29.775
Vac = 49.638	ic = 2.23	Vcn = 28.898

θ_{AB} = 119.51
θ_{BC} = 122.77 not within specification - 5.84 difference
θ_{AC} = 116.93

Third try with split neutral:

Vab = 51.007	ia = .692	Van = 29.249
Vbc = 51.440	ib = .692	Vbn = 29.768
Vac = 49.564	ic = 2.22	Vcn = 28.903

θ_{AB} = 119.6
θ_{BC} = 122.5 not within specification - 5.6 difference
θ_{AC} = 116.9

Switched leads (red to black) and impedance in neutral 21 turns on iron core:

Vab = 50.793	Van = 29.009
Vbc = 50.734	Vbn = 29.663
Vac = 48.963	Vcn = 28.352

θ_{AB} = 119.92
θ_{BC} = 121.95 not within specification - 4.75 difference
θ_{AC} = 117.2

1/2 turns taken off channel iron core. Leads - black to red.

Vab = 50.411	ia = .740	Van = 28.865
Vbc = 50.630	ib = .738	Vbn = 29.424
Vac = 48.881	ic = 2.17	Van = 28.399

θ_{AB} = 119.73
θ_{BC} = 122.22   not within specification - 5.01 difference
θ_{AC} = 117.2

<u>30 turns put on iron core</u>:

Vab = 50.795	ia = .747	Van = 28.978
Vbc = 50.792	ib = .710	Vbn = 29.717
Vac = 48.960	ic = 2.16	Vcn = 28.400

θ_{AB} = 119.85
θ_{BC} = 121.83   not within specification - 4.7 difference
θ_{AC} = 117.14

<u>Rebalance</u>

ia = .762	Vab = 50.940	Van = 29.023
ib = .788	Vbc = 50.806	Vbn = 29.780
ic = 2.25	Vac = 48.959	Vcn = 28.370

θ_{AB} = 120.05
θ_{BC} = 121.77   not within specification - 4.68 difference
θ_{AC} = 117.09

<u>4-4-77</u>   <u>Unbalance Test</u> - Phase C heavily loaded.

Van = 116.5	Vab = 203	Van = 116.5	Vab = 203
Vbn = 118	Vbc = 204	Vbn = 118.5	Vbc = 204
Vcn = 114.5	Vac = 197	Vcn = 115	Vac = 197.5

at load.

$$\text{Cos } \theta_{AB} = - \frac{Vab^2 - Van^2 - Vbn^2}{2\ VanVbn}$$

<u>at load</u>

θ_{AB} = 119.92
θ_{BC} = 122.66   5.62 difference
θ_{AC} = <u>117.04</u>
359.62

<u>at terminals</u>

θ_{AB} = 119.63
θ_{BC} = 121.77   4.66 difference
θ_{AC} = <u>117.11</u>
358.51

New measurements without meter impedance:

ia = .716	Van = 115.8	Vab = 203
ib = .710	Vbn = 118.6	Vbc = 205
ic = 2.20	Vcn = 114.8	Vac = 197.5

Θ_{AB} = 120.00

Θ_{BC} = 122.87   5.03 difference

Θ_{AC} = 117.84
360.7

Second trial using digital voltmeter:

Van = 29.308 x 4	Vab = 51.138 x 4
Vbn = 29.863	Vbc = 51.630
Vcn = 29.004	Vac = 49.745

Θ_{AB} = 119.59

Θ_{BC} = 122.57   5.47 difference

Θ_{AC} = 117.10
359.26

Reduced current on Phase C:

ia = .717	Vac = 49.784	Van = 29.315
ib = .710	Vbc = 51.590	Vbn = 29.848
ic = 2.14	Vab = 51.109	Vcn = 29.025

Θ_{AB} = 119.50

Θ_{BC} = 122.39   5.24 difference

Θ_{AC} = 117.15
359.04

Phase B heavily loaded:

ia = .74	Van = 29.664	Vab = 51.349
ib = 2.07	Vbn = 28.997	Vbc = 49.885
ic = .71	Vcn = 29.401	Vac = 51.068

Θ_{AB} = 122.17

Θ_{BC} = 117.35   4.82 difference

Θ_{AC} = 119.68
359.2

Phase A heavily loaded:

ia = 2.1	Van = 28.224	Vab = 48.602
ib = .70	Vbn = 28.749	Vbc = 50.061
ic = .70	Vcn = 29.140	Vac = 50.240

θ_{AB} = 117.09
θ_{BC} = 119.72   5.18 difference
θ_{AC} = 122.27
359.08

Added another neutral line to decrease neutral impedance:

Phase A heavily loaded (red to black)

ia = 2.1	Van = 28.256	Vab = 48.633
ib = .705	Vbn = 28.739	Vbc = 50.091
ic = .70	Vcn = 29.165	Vac = 50.280

θ_{AB} = 117.14
θ_{BC} = 119.5   5.09 difference
θ_{AC} = 122.23
358.87

(black to red)

Van = 28.245	Vab = 48.616
Vbn = 28.724	Vbc = 50.069
Vcn = 29.154	Vac = 50.314

θ_{AB} = 117.16
θ_{BC} = 119.78   5.29 difference
θ_{AC} = 122.45
359.39

Rebalanced: (black to red) - Phase B heavily loaded

Van = 29.699	Vab = 51.392
Vbn = 29.038	Vbc = 49.923
Vcn = 29.396	Vac = 51.102

θ_{AB} = 122.07
θ_{BC} = 117.37   4.7 difference
θ_{AC} = 119.71
359.15

4-8-77   Voltage:

3.4

average 3.8

4.2

Full Load - Unity Power Factor

Van = 118.0 ia = 2.3
Vbn = 118.5 ib = 2.2
Vcn = 118.5 ic = 2.2

DVM 4.0 volts

Peak 4.4 minimum 3.45 average 3.925

4-11-77 Unbalance Test - Phase A, 10K - Phases B and C, 8.5K

ia = 1.80 x 40
ib = 1.80 x 40
ic = 2.15 x 40

Vab = 50.456 Van = 29.00
Vbc = 50.700 Vbn = 29.349
Vac = 50.074 Vcn = 29.086

Θ_{AB} = 119.7
Θ_{BC} = 120.37 1.15 difference
Θ_{AC} = 119.1

Phase A, OK - Phases B and C, 1.5K

Vab = 50.400 Van = 29.151 ia = .31
Vbc = 50.390 Vbn = 29.145 ib = .305
Vac = 50.400 Vcn = 29.304 ic = 0

Θ_{AB} = 119.66
Θ_{BC} = 119.11 .55 difference
Θ_{AC} = 119.13

1/2 load on Phases A and B - Full load on Phase C with instruments in

ia = 1.08
ib = 1.08
ic = 2.15

Vab = 50.999 Van = 29.239
Vbc = 51.385 Vbn = 29.740
Vac = 49.856 Vcn = 29.052

Θ_{AB} = 119.69
Θ_{BC} = 121.85 4.27 difference
Θ_{AC} = 117.58

With instruments out

Vab = 51.013	Van = 29.271
Vbc = 51.381	Vbn = 29.733
Vac = 49.967	Vcn = 29.093

θ_{AB} = 119.66

θ_{BC} = 121.71 3.94 difference

θ_{AC} = 117.77

SECTION	REQUIREMENT
5.1.1.4	Phase Sequence: The phase sequence is A - B - C corresponding to phase wire markings, Figure 1. Result: Phase sequence A - B - C/same as markings.
5.1.1.5	AC Waveform Distortion: The distortion factor for the phase voltage waveform shall not exceed .05 nor shall the limits of the AC distortion spectrum exceed the envelope in Figure 2. The crest factor shall not exceed 1.41 ± .10 nor shall the D.C. component exceed ± .10 volts. Excepting the conditions of spikes and surges, the waveform shall be within the band V (± .071 + sinθ) where V is the maximum value of the equivalent sine wave and θ is the phase angle. Test Method: Mil-Std-705, Section 601 Mil-Handbook 705, Section 106, 205 Results: As follows:

AC WAVEFORM ANALYSIS

2-22-77 Trial One

Van = 120.2 ia = 2.10 x 40
Vbn = 120.8 ib = 2.15 x 40
Vav = 120.3 iav = 2.13 x 40

P_1 = 360 P_2 = 385

3 x 120.3 x 2.13 x 40 = KVA = 30748.7

29,800 = KW

$$P.F. = \frac{29,800}{30,748.7} = .97$$

Trial Two

Van = 115.0 ia = 2.08 x 40
Vbn = 115.0 ib = 2.16 x 40
Vcn = 114.5 ic = 2.15 x 40
Vav = 115.0 iav = 2.13 x 40

P_1 = 350 P_2 = 350

KVA = 3 x 115 x 2.13 x 40 = 29,394

KW = (350 + 380) 40 = 29,200

$$P.F. = \frac{29,200}{29,394} = .99$$

Raised current:

Van = 115.0 ia = 2.15 x 40
Vbn = 115.5 ib = 2.20 x 40
Vcn = 114.5 ic = 2.20 x 40
Vav = 115.0 iav = 2.18 x 40

KVA = 30,840

KW = 30,280

P_1 = 362 P_2 = 395 P.F. = .98

Waveform Analysis: The AC waveform distortion shall not exceed 0.05 and the crest factor shall not exceed 1.41 ± .1, nor shall the DC component exceed ± 0.10 volts.

Line to neutral - no load.

HARMONIC NUMBER	Van	Van		HARMONIC NUMBER	Van	Van	
1	*0	0	1	26	-75	-80	.0001
2	-56	-56	.00158	27	-79	-83	.0007
3	-57	-58	.00126	28	-76	-	-
4	-64	-66	.0005	29	-77	-81	.00009
5	-46	-46	.00501	30	-77	-	-
6	-75	-	-	31	-82	-	-
7	-52	-52	.00251	32	-76	-	-
8	-65	-65	.00056	33	-81	-	-
9	-72	-74	.00020	34	-76	-	-
10	-70	-74	.00020	35	-72	-70	.00032
11	-50	-50	.00316	36	-76	-	-
12	-76	-	-	37	-77	-82	.00008
13	-54	-53	.00224	38	-77	-	-
14	-76	-76	.00016	39	-	-84	.00006
15	-	-80	.0001	40	-77	-	-
16	-78	-84	.00006	41	-	-84	.00006
17	-63	-64	.00063	42	-78	-	-
18	-76	-	-	43	-86	-84	.00006
19	-54	-54	.002	44	-76	-	-
20	-76	-	-	45	-84	-84	.00006
21	-84	-80	.0001	46	-79	-	-
22	-76	-83	.00007	47	-82	-85	.00006
23	-73	-80	.0001	48	-77	-	-
24	-77	-	-	49	-84	-	-
25	-78	-77	.00014	50	-79	-	-

*First trial figures inaccurate. White noise interference.

Distortion Factor - 0.00750

2-22-77 Line to neutral - no load.

HARMONIC NUMBER	Vbn		Vcn	
1	1	0	1	0
2	.00158	-56	.00141	-57
3	.00200	-54	.00251	-52
4	.00056	-65	.00056	-65
5	.00631	-44	.00631	-44
6	.00010	-80	-	-
7	.00316	-50	.00447	-47
8	.00079	-62	.00063	-64
9	.00398	-48	.01259	-38
10	.00020	-74	-	-
11	.00251	-52	.00100	-60
12	.00010	-80	-	-
13	.00251	-52	.00251	-52
14	.00014	-77	.00016	-76
15	.00032	-70	.00050	-66
16	.00006	-84	.00008	-82
17	.00089	-61	.00071	-63
18	.00008	-82	-	-
19	.00020	-54	.00158	-56
20	-	-	-	-
21	.00018	-75	.00016	-76
22	-	-	-	-
23	.00022	-73	.00014	-77
24	-	-	-	-
25	.00008	-82	.00010	-80
26	.00007	-83	.00008	-82
27	.00013	-78	.00008	-82
29	-	-	.00022	-73
31	.00008	-82	-	-
33	.00007	-83	.00008	-82
35	.00063	-64	.00032	-70
37	.00013	-78	.00010	-80
39	-	-	.00006	-85
Distortion Factor	.00934		.01543	

2-22-77 Line to Line - no load.

HARMONIC NUMBERS	V_{AB}		V_{AC}		V_{BC}	
1	0	1	0	1	0	1
2	-58	.00126	-58	.00126	-57	.00141
3	-57	.00141	-54	.00200	-54	.00200
4	-66	.00050	-66	.00050	-66	.00050
5	-45	.00562	-36	.01585	-44	.00631
6	-	-	-	-	-	-
7	-54	.00200	-50	.00316	-48	.00398
8	-65	.00056	-66	.00050	-63	.00071
9	-54	.00200	-53	.00224	-47	.00447
10	-73	.00022	-76	.00016	-	-
11	-51	.00282	-54	.00200	-60	.00100
12	-	-	-	-	-	-
13	-54	.00200	-54	.00200	-52	.00251
14	-79	.00011	-76	.00016	-76	.00016
15	-76	.00016	-71	.00028	-66	.00050
16	-	-	-	-	-	-
17	-64	.00063	-65	.00056	-64	.00063
18	-	-	-	-	-	-
19	-54	.00200	-56	.00158	-56	.00158
20	-	-	-	-	-	-
21	-77	.00014	-76	.00016	-76	.00016
22	-	-	-	-	-	-
23	-73	.00022	-78	.00013	-76	.00016
24	-	-	-	-	-	-
25	-78	.00013	-78	.00013	-	-
26	-80	.00010	-	-	-	-
27	-80	.00010	-	-	-80	.00010
29	-84	.00006	-83	.00007	-	-
31	-85	.00006	-	-	-81	.00009
33	-86	.00005	-	-	-82	.00008
35	-73	.00022	-71	.00028	-73	.00022
37	-80	.00010	-82	.00008	-80	.00010
39	-	-	-84	.00006	-	-
Distortion Factor		.00777		.01683		.00966

2-22-77 Line to Neutral - full load, unity power factor

HARMONIC NUMBERS	Van		Vbn		Vcn	
1	0	1	0	1	0	1
2	-55	.00178	-55	.00178	-55	.00178
3	-76	.00016	-50	.00316	-49	.00355
4	-70	.00032	-70	.00032	-70	.00032
5	-50	.00316	-45	.00562	-46	.00501
6	-	-	-	-	-	-
7	-44	.00631	-50	.00316	-50	.00316
8	-70	.00032	-65	.00056	-66	.00050
9	-68	.00040	-50	.00316	-51	.00282
10	-74	.00020	-		-74	.00020
11	-55	.00178	-50	.00316	-55	.00178
12	-	-	-	-	-	-
13	-56	.00158	-56	.00158	-60	.00100
14	-80	.00010	-	-	-80	.00010
15	-	-	-72	.00025	-72	.00025
16	-	-	-	-	-	-
17	-70	.00032	-66	.00050	-66	.00050
18	-	-	-	-	-	-
19	-48	.00398	-58	.00126	-60	.00100
20	-	-	-	-	-	-
21	-	-	-80	.00010	-80	.00010
22	-	-	-	-	-	-
23	-80	.00010	-84	.00006	-77	.00014
24	-	-	-	-	-	-
25	-	-	-82	.00008	-83	.00007
26	-	-	-	-	-	-
27*	-	-	-	-	-83	.00007
29	-	-	-	-	-	-
31	-	-	-	-	-	-
33	-	-	-	-	-	-
35	-80	.00010	-78	.00013	-80	.00010
37	-84	.00006	-84	.00006	-86	.00005
Distortion Factor		.00866		.0089		.0080

2-22-77 Line to Line - Full Load, Unity Power Factor

HARMONIC NUMBERS	V_{AB}		V_{BC}		V_{AC}	
1	0	1	0	1	0	1
2	-55	.00158	-54	.00158	-55	.00178
3	-56	.00158	-54	.00200	-55	.00178
4	-70	.00032	-71	.00028	-71	.00028
5	-38	.01259	-37	.01413	-39	.01122
6	-	-	-	-	-	-
7	-54	.00200	-39	.01122	-43	.00708
8	-68	.00040	-66	.00050	-69	.00035
9	-56	.00158	-50	.00316	-56	.00158
10	-80	.00010	-76	.00016	-74	.00020
11	-52	.00251	-52	.00251	-56	.00158
12	-82	.00008	-	-	-	-
13	-55	.00178	-59	.00112	-57	.00141
14	-83	.00007	-	-	-	-
15	-76	.00016	-72	.00025	-80	.00010
16	-83	.00007	-	-	-	-
17	-70	.00032	-67	.00045	-68	.00040
18	-	-	-	-	-	-
19	-60	.00100	-60	.00100	-60	.00100
20	-	-	-	-	-	-
21	-	-	-80	.00010	-84	.00006
22	-	-	-	-	-	-
23	-	-	-82	.00008	-77	.00014
24	-	-	-	-	-	-
25	-	-	-83	.00007	-84	.00006
26	-	-	-	-	-	-
27	-	-	-83	.00007	-	-
29	-	-	-84	.00006	-	-
31	-	-	-	-	-	-
33	-	-	-	-	-	-
35	-80	.00010	-80	.00001	-80	.00010
37	-86	.00005	-83	.00007	-	-
Distortion Factor		.01347		.01874		.01381

2-23-77 Harmonic Tests - AC Waveform Analysis - .8 Power Factor

V_{AB} = 202 ia = 2.69 P_1 = 200 P.F. = .80
V_{BC} = 200 ib = 2.72 P_2 = 550
V_{CA} = 200 ic = 2.70

Line to Neutral - .8 power factor

HARMONIC NUMBERS	V_{AN}		V_{BN}		V_{CN}	
1	0	1	0	1	0	1
2	-55	.00178	-54	.00200	-54	.00200
3	-48	.00398	-51	.00282	-62	.00079
4	-74	.00020	-72	.00025	-72	.00025
5	-49	.00355	-48	.00398	-50	.00316
6	-	-	-	-	-	-
7	-49	.00355	-50	.00316	-55	.00178
8	-52	.00251	-65	.00056	-68	.00040
9	-47	.00447	-49	.00355	-75	.00018
10	-	-	-	-	-79	.00011
11	-50	.00316	-54	.00200	-54	.00200
12	-	-	-	-	-	-
13	-53	.00224	-52	.00251	-54	.00200
14	-80	.00010	-80	.00010	-	-
15	-70	.00032	-68	.00040	-80	.00010
16	-	-	-	-	-	-
17	-68	.00040	-64	.00063	-68	.00040
18	-	-	-	-	-	-
19	-60	.00100	-59	.00112	-58	.00126
20	-	-	-	-	-	-
21	-75	.00018	-79	.00011	-	-
22	-	-	-	-	-	-
23	-75	.00018	-75	.00018	-82	.00008
24	-	-	-	-	-	-
25	-	-	-82	.00008	-	-
27	-82	.00008	-82	.00008	-	-
29	-	-	-	-	-	-
31	-84	.00006	-	-	-85	.00006
33	-81	.00009	-82	.00008	-80	.00010
Distortion Factor		.00932		.00793		.00528

<u>2-23-77</u> Line to Line - Full Load - .8 power factor

HARMONIC NUMBERS	Vac		Vbc		V_{AB}	
1	0	1	0	1	0	1
2	-48	.00398	-48	.00398	-49	.00355
3	-47	.00447	-45	.00562	-50	.00316
4	-	-	-65	.00056	-65	.00056
5	-45	.00562	-42	.00794	-44	.00631
6	-	-	-	-	-	-
7	-46	.00501	-44	.00631	-50	.00316
8	-	-	-64	.00063	-64	.00063
9	-49	.00355	-41	.00891	-48	.00398
10	-	-	-	-	-	-
11	-54	.00200	-58	.00126	-47	.00447
12	-	-	-	-	-	-
13	-50	.00316	-50	.00316	-48	.00398
14	-	-	-78	.00013	-	-
15	-70	.00032	-66	.00050	-69	.00035
16	-	-	-	-	-	-
17	-65	.00056	-64	.00063	-60	.00100
18	-	-	-	-	-	-
19	-54	.00200	-59	.00112	-53	.00224
20	-	-	-	-	-	-
21	-74	.00020	-75	.00018	-79	.00011
22	-	-	-	-	-	-
23	-76	.00016	-74	.00020	-74	.00020
24	-	-	-	-	-	-
25	-78	.00013	-80	.00010	-80	.00010
26	-	-	-	-	-	-
27	-79	.00011	-84	.00006	-	-
29	-82	.00008	-	-	-	-
31	-80	.00010	-82	.00008	-	-
33	-84	.00006	-84	.00006	-	-
35	-75	.00018	-81	.00009	-77	.00014
37	-	-	-85	.00006	-82	.00008
Distortion Factor		.01112		.01562		.01145

2-23-77

CREST FACTOR ANALYSIS

Line to Neutral - full load - .8 power factor

AN $\frac{118}{54.35} = 2.17$ Vpeak = 3 volts
crest = 1.38

BN $\frac{120}{54.35} = 2.21$ Vpeak = 3 volts
crest = 1.36

CN $\frac{118}{54.35} = 2.17$ Vpeak = 3 volts
crest = 1.38

Line to Line - Full Load - .8 power factor

AC $\frac{200}{54.35} = 3.68$ Vpeak = 5.0
crest = 1.36

AB $\frac{201}{54.35} = 3.7$ Vpeak = 5.1
crest = 1.38

BC $\frac{201}{54.35} = 3.7$ Vpeak = 5.1
crest = 1.38

Final Voltages:				
	V_{AC} = 199V	V_{AN} = 115.8	Ia = 2.70	P_1 = 199
	V_{AB} = 201V	V_{BN} = 116	Ib = 2.70	
	V_{BC} = 201V	V_{CN} = 115.8	Ic = 2.72	P_2 = 550

Line to Neutral - no load - use 54.35 ratio volt per inch

A-N $\frac{114.6}{54.35} = 2.11''$ Vpeak = 3" crest = $\frac{3}{2.11} = 1.42$

B-N $\frac{115.6}{54.35} = 2.13''$ Vpeak = 3" crest = $\frac{3}{2.11} + 1.41$

C-N $\frac{114.2}{54.35} = 2.10$ Vpeak = 3" crest = 1.43

Line to Line - no load.

A-B $\frac{200}{54.35} = 3.68$ Vpeak = 5.2V crest = 1.41

A-C $\frac{200}{54.35} = 3.68$ Vpeak = 5.2V crest = 1.41

B-C $\frac{201}{54.35} = 3.70$ Vpeak = 5.1V crest = 1.38

2-23-77

Line to Neutral - full load - unity power factor.

A-N $\frac{114.6}{54.35} = 2.11$ Vpeak = 3V crest = 1.42

B-N $\frac{115.6}{54.35} = 2.13$ Vpeak = 3V crest = 1.41

C-N $\frac{114.2}{54.35} = 2.10$ Vpeak = 3V crest = 1.43

Line to Line - full load - unity power factor.

Vca $\frac{199.0}{54.35} = 3.66$ Vpeak = 5.1V crest = 1.39

Vab $\frac{198.0}{54.35} = 3.64$ Vpeak = 5.1V crest = 1.40

Vcb $\frac{201.0}{54.35} = 3.70$ Vpeak = 5.1V crest = 1.38

SECTION	REQUIREMENT
5.1.1.6	Amplitude Modulation: The amplitude modulation components (side bands) resulting from all modulation influences shall not exceed 0.62 volts RMS over the range 400 $\pm$ 60 HZ.

(1) Test Method: Mil-Std-705, Section 602
Mil-Handbook 705, Section 106

(2) Theory: As follows:

$V = (V_{max} \cos W_s t) \cos Wt$

$W = 400$ HZ $\quad W_S$ = modulating frequency

$1/2\ V_{max} \cos (W + W_S)t + 1/2\ V_{max} \cos (W - W_S)t$

$$40 = 20 \log_{10} \frac{V_n}{V_1} \qquad \log_{10} \frac{V_n}{V_1} = 2 \qquad \frac{V_n}{V_1} = 100$$

$$20 \log_{10} 1/2 = -6.02$$

115

340 400 460

40db below 115 volts = 1.15 volts

$20 \log_{10} .0571 \qquad 20 \log_{10} 1/2 - 20 \log_{10} 10.0 = -26.02$

$$V(t) = V_{max} \left(1 + \frac{V_S}{V_{max}} \cos W_S t\right) \cos Wt$$

$$V(t) = V_{max} \cos Wt + 1/2 V_S \cos (W + W_S)t + 1/2 V_S \cos (W - W_S)t$$

$1/2V_s$ = amplitude of side band .62 volts

$$db = 20 \log_{10} \frac{V_n}{V_1} = 20 \log_{10} V_n - 20 \log_{10} 115$$

$$-56 + 20 \log_{10} 115 = -56 + 41 = -15$$

Result: Requirement removed from Mil-Std

SECTION	REQUIREMENT
5.1.1.7	System Frequency: Shall be 400 $\pm$ 5 HZ for helicopters 400 $\pm$ 20 HZ. Emergency mode 400 $\pm$ 40 HZ. Below 360 HZ, frequency/voltage ratio shall be greater than 2.9.

(1) Test Method: Mil-Std-705, Section 608
Mil-Handbook 705, Section 205

(2) Results: As follows:

FREQUENCY CALIBRATION

FREQUENCY	DIVISIONS FROM 1-10-77-7
400.84	46.5
404.54	45.0
408.83	44.0
413.45	43.5
395.96	47.0
391.85	48.0
387.67	49.0

FREQUENCY DIFFERENCE

FREQUENCY Div	Hertz	CYCLES	MILLISECONDS
46.5	400	0	0
44	411	2	5
43	416	4	10
43	416	6	15
44	411	8	20
44.5	409	10	25
46	402	12	30
46	402	14	35
46.5	400	16	40
46.5	400	18	45
46.5	40	20	50

$$\cos = \frac{(\ \ (325 + 200)\ 40}{V3 \times 217 \times 40 \times 155} \qquad .9 = \frac{21}{25.303}$$

$$\tan = V3\ \frac{P_1 - P_2}{P_1 + P_2} \qquad .75 = \tan = V3\ \frac{1 - \frac{P_2}{P_1}}{1 + \frac{P_2}{P_1}} = V3\ (1 - \frac{P_2}{P_1})$$

$$(3/4 + V3)\frac{P_2}{P_1} = V3 - 3/4 \qquad \frac{P_2}{P_1}\ \frac{V3 - 3/4}{V3 + 3/4}\ \frac{.98205}{2.482} = .39566$$

$$V = 200 \qquad P = V3\ VI \cos \Theta \qquad P = 30000 = V3 \times 200 \times .8I = \frac{17320}{160} = 110$$

$$\frac{110}{40} = 2.75$$

$$V = 200 \qquad I = 2.75 \times 40 \qquad P = \begin{matrix}245\\ \underline{555}\\ 800\end{matrix} \qquad \frac{800 \times 40}{1000} = 32.000$$

$$\frac{V3 \times 200 \times 2.75 \times 40}{32000} = \frac{1}{.84}$$

V = 200   I = 2.75 x 40   P = 198 $\frac{738 \times 40}{1000}$ = 29.5

540
738

$\frac{29.5}{V3 \times 200 \times 2.73 \times 40} = \frac{29.5}{38}$

Microseconds	f in HZ		
2500.2	399.97		
2499.0	400.15		
2497.3 load	400.43	.67	.16%
2501.5	399.76		
2497.2 no load	400.448	.752	.188%
2501.9	399.696		
2502.3			
2504 transient			
2508.8	399.872	.136	.34%
2499.5	400.008		

Voltage 124.7/8

	Volts	Period	Frequency	Dig		
1	124.7/6	2502.0	400	399.08	400.12	65.7
		2496.5		400.56		
2	124.5/6	2475.4	404	400.56	402.65	64.2
		2471.0		404.69		
3	124.5/6	2445.1	408		408.86	63.0
		6.5				
4	124.4/5	2419.1	412		413.76	
		4.6				
5	124.6/7	2525.4	396		395.86	
		6.9				
6	124.6/7	255.20	392		392.11	67.0
		4.86				
7	124.5	258.34	388		387.51	
		7.77				

SECTION	REQUIREMENT
5.1.1.8	Frequency Modulation: Modulated frequency deviation shall not exceed the limits specified in Figure 3. (1) Test Method: Mil-Std-705, Section 608 Mil-HDBK-705, Section 205 (2) Results: Did not test no frequency modulation in voltage only contribution of frequency modulation would come from defective governor circuits.
5.1.1.9	Frequency Drift: Frequency drift: Frequency drift shall not exceed the steady state limits, nor occur at a rate of change exceeding 15 HZ per minute. (1) Results: Frequency drift exceeded 15HZ per minute when system was exposed to inclement weather. When environment was held constant, no drift was observed.
5.1.2.1.	Voltage Surge: Voltage surges shall not exceed the limits of Figure (Return to steady state limits within 80 milliseconds) (1) Result: From visicorder recordings no load to full load 64 milliseconds.
5.1.2.2	Voltage Spike: The system electromagnetic capability aspects of voltage shall be controlled by Mil-E-6051. (1) Result: Did not test. Requirement removed from Mil-Std.
5.1.3.	Frequency Transient Limits: The frequency transient shall be within 400 $\pm$ 25HZ, returning to within $\pm$ 20HZ in one second, to within 400 $\pm$ 10 HZ in 5 seconds, and to within 400 $\pm$ 5 HZ in 15 seconds. The rate of frequency change shall not exceed 500HZ/second for any period greater than 15 milliseconds. (1) Results: From visicorder data - no load/full load frequency response was as follows: (a) No load to full load, 400HZ to 388 HZ returning in less than one second. (b) Full load to no load, 400HZ to 412HZ returning to 400HZ in less than one second.
5.1.4	Over Hase and Overvoltage: The AC overvoltage may not exceed 180 volts. The under voltage may not go below 10 volts. (1) Results: Under voltage cutoff - 95 volts Over voltage cutoff - 150 volts

SECTION	REQUIREMENT
5.1.5	Out-of-Tolerance Frequency: The frequency limits shall not exceed 400 ± 25HZ for more than 5 seconds, or for an interval specifically authorized, but in no instance be allowed to exceed 480HZ.

Results: (1) Under frequency shutdown at 370.37HZ.

(2) Overfrequency shutdown: System still operational at 421HZ; could not obtain higher frequency to observe generator shutdown.

APPENDIX E

GENERATOR CALCULATIONS

Formulas presented are for 100% load calculations.

These items can be recalculated for any load condition by simply inserting the values that correspond to the % load being calculated. The factor $\frac{(\%\ \text{Load})}{100}$ takes care of (I_{PH}) as it changes with load.

Note that values for F & W and W_C (Stator Core Loss) do not change with load, therefore they can be calculated only once.

See Ref (a), (b), (h), (k), and (l) for calculation procedures.

E_{PH} **PHASE VOLTS**

For 3 phase, wye connected generator

$$E_{PH} = \frac{(\text{Line Volts})}{\sqrt{3}}$$

ℓ_s **SOLID CORE LENGTH**

The solid length is the gross length times the stacking factor. If ventilating ducts are used, their length must be subtracted from the gross length also.

$$\ell_s = (K_i)\left[(\ell) - (n_v)(b_v)\right]$$

τ_P **POLE PITCH** in inches.

$$\tau_P = \frac{\pi(d)}{(P)}$$

K_{SK} **SKEW FACTOR**

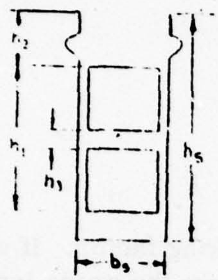
The skew factor is the ratio of the voltage induced in the coils to the voltage that would be induced if there were no skew.

When $_{SK} = 0,\ K_{SK} = 1$

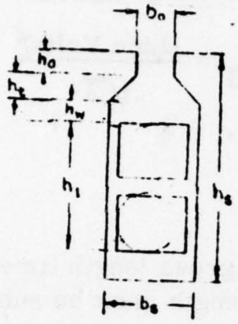
$$K_{SK} = \frac{\sin\left[\dfrac{\pi(\tau_{SK})}{2(\tau_P)}\right]}{\dfrac{\pi(\tau_{SK})}{2(\tau_P)}}$$

TYPE OF STATOR SLOT

(Q) Open Slots



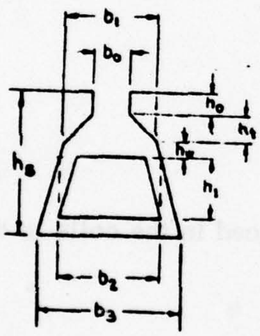
(b) Constant Slot Width



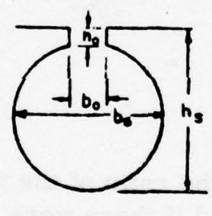
*NOTE:
For slot type C,

$$b_s = \frac{(b_1) + (b_3)}{2}$$

*(C) Constant Tooth Width



(d) Round Slots



b_0, b_1, b_2, b_3, b_s, h_0, h_1, h_2, h_3, h_s, h_t, h_w — **ALL SLOT DIMENSIONS** - Given in inches.

Where the dimension does not apply to the slot being used, insert 0 on input sheet.

For slot type C

$$b_s = \frac{(b_1) + (b_3)}{2}$$

Q **STATOR SLOTS** - Number of

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h_c **DEPTH BELOW SLOTS**

The depth of the stator core below the slots (in inches. Due to mechanical strength reasons, h_c should never be less than 70% of h_s.

$$h_c = \frac{(D) - \left[(d) + 2(h_s)\right]}{2}$$

q **SLOTS PER POLE PER PHASE**

$$q = \frac{(Q)}{(P)\ (m)}$$

τ_s **STATOR SLOT PITCH, inches**

$$\tau_s = \frac{\pi\ (d)}{(Q)}$$

$\tau_s 1/3$ **STATOR SLOT PITCH**

1/3 distance up from narrowest section

For slot (a), (b), (c), and (e) - (in inches)

$$\tau_s 1/3 = \frac{\pi \left[(d) + .66(h_s)\right]}{(Q)}$$

For slot (d)

$$\tau_s 1/3 = \frac{\pi \left[(d) + 2(h_0) + 1.32(b_s)\right]}{(Q)}$$

PER UNIT OF POLE PITCH SPANNED

Ratio of the number of slots spanned to the number of slots in a pole pitch. This value must be between 1.0 and 0.5 to satisfy the limits of this program.

$$\frac{(Y)}{(m)\ (q)}$$

K_P **PITCH FACTOR**

The ratio of the voltage induced in the coil to the voltage that would be induced in a full pitched coil.

$$K_P = \sin\left[\frac{(Y)}{(m)(q)} \times 90^\circ\right]$$

n_e **TOTAL EFFECTIVE CONDUCTORS**

The actual number of effective series conductors in the stator winding taking into account the pitch and skew factors but not allowing for the distribution factor.

$$n_e = \frac{(Q)(n_s)(K_P)(K_{SK})}{(C)}$$

a_c **CONDUCTOR AREA OF STATOR WINDING** in(inches)^2

The actual area of the conductor taking into account the corner radius on square and rectangular wire. See the following table for typical values of corner radii.

$$a_c = .25\pi(\text{Dia})^2$$

For 60° phase belt angle and q = integer

$$K_d = \frac{\text{Sin } 30^\circ}{(q)\ \text{Sin}\left[30/(q)\right]}$$

For 60° phase belt angle and (q) ≠ integer = N/B reduced to lowest terms.

$$K_d = \frac{\text{Sin } 30^\circ}{(N)\ \text{Sin}\left[30/(N)\right]}$$

For 120° phase belt angle and (q) = integer

$$K_d = \frac{\text{Sin } 60^\circ}{2(q)\ \text{Sin}\left[30/(q)\right]}$$

For 120° phase belt angle and $q \neq$ integer

$$K_d = \frac{\sin 60^\circ}{2(N) \sin \left[30/(N)\right]}$$

S_S **CURRENT DENSITY**

Amperes per square inch of stator conductor.

$$S_S = \frac{(I_{PH})}{(C)(a_c)}$$

L_E **END EXTENSION LENGTH** in inches

$$L_E = \frac{.5 + K_T \pi y \left[d + h_s\right]}{Q}$$

$$L_E = 2\left(\ell_{e2}\right) + \pi\left[\frac{h_1}{2} + (d_b)\right] + y\left[\frac{\tau}{\sqrt{\tau_s^2 - b_s^2}}\right]$$

ℓ_t **1/2 MEAN TURN**

The average length of one conductor in inches.

$$\ell_t = (\ell) + (L_E)$$

X_s °C **STATOR TEMP °C**

Input temp at which F. L. losses will be calculated. No load losses and cold resistance will be calculated at 20°C.

ρ_s **RESISTIVITY OF STATOR WINDING**

In micro ohm-inches at 20°C. If tables are available using units other than that given above, use factors below for conversion to ohm-inches.

ρ		ohm-cm	ohm-in	ohm-cir mil/ft
1 ohm-cm	=	1.000	0.3937	6.015×10^{6}
1 ohm-in	=	2.540	1.000	1.528×10^{7}
1 ohm-cir mil/ft	=	1.662×10^{-7}	6.545×10^{-8}	1.000

Conversion Factors for Electrical Resistivity

ρ_S (hot) **RESISTIVITY OF STATOR WINDING**

Hot at X_s°C in micro ohm-inches

$$\rho_{S(hot)} = (\rho_S)\left[\frac{(X_s\,^\circ C) + 234.5}{254.5}\right]$$

R_{SPH} (cold) **STATOR RESISTANCE/PHASE**

Cold at 20°C in ohms

$$R_{SPH(cold)} = \frac{(\rho_s)(n_s)(Q)(\ell_t)}{(m)(a_c)(C)^2} \times 10^{-6}$$

R_{SPH} (hot) **STATOR RESISTANCE/PHASE**

Calculated at X°C in ohms

$$R_{SPH(hot)} = \frac{(\rho_{s\ hot})(n_s)(Q)(\ell_t)}{(m)(a_c)(C)^2} \times 10^{-6}$$

EF (top) **EDDY FACTOR TOP**

The eddy factor of the top coil. Calculate this value at the expected operating temperature of the machine.

$$EF_{top} = 1 + \left\{ .584 + \left[\frac{(N_{st})^2 - 1}{16}\right]\left[\frac{(h'_{st})\ (\ell)}{(h_{st})\ (\ell_t)}\right]^2 \right\} 3.35 \times 10^{-3}$$

$$\left[\frac{(h_{st})(n_s)(f)(a_c)}{(b_s)(\rho_S)_{hot}}\right]^2$$

EF (bot) **EDDY FACTOR BOTTOM**

The eddy factor of the bottom coil at the expected operating temperature of the machine.

$$EF_{(bot)} = (EF_{(top)}) - 1.677 \left[\frac{(h_{st})(n_s)(f)(a_c)}{(b_s)(\rho_{S\,hot})}\right]^2 \times 10^{-3}$$

b_{tm} **STATOR TOOTH WIDTH**

1/2 way down tooth in inches.

For slots type (a), (b), (d) and (e)

$$b_{tm} = \frac{\pi\left[(d) + (h_s)\right]}{(Q)} - (b_s)$$

For slot type (c)

$$b_{tm} = \frac{\pi\left[(d) + 2(h_s)\right]}{(Q)} - (b_3)$$

$b_{t\,1/3}$ **STATOR TOOTH WIDTH**

1/3 distance up from narrowest section

For slots type (a), (b) and (e)

$$b_{t\,1/3} = (\tau_{s\,1/3}) - (b_s)$$

For slot type (c)

$$b_{t\,1/3} = b_{tm}$$

For slot type (d)

$$b_{t\,1/3} = (\tau_{1/3}) - \frac{2\sqrt{2}}{3}(b_s)$$

b_t **TOOTH WIDTH AT STATOR I.D. in inches**

For partially closed slot

$$b_t = \frac{\pi(d)}{(Q)} - \left(b_0\right)$$

For open slot

$$b_t = \frac{\pi(d)}{(Q)} - \left(b_s\right)$$

g_{min} **MINIMUM AIR GAP in inches**

For concentric pole face $g_{min} = g_{max}$.

For non concentric pole face g_{min} **= gap at the center of pole.**

C_X REACTANCE FACTOR

Used in calculating conductor permeance and is dependent on the pitch and distribution factor.

$$C_X = \frac{(K_X)}{(K_P)^2\,(K_d)^2}$$

K_X Factor to account for difference in phase current in coil sides in same slot.

For 60° phase belt winding

$$K_X = 1/4\left[\frac{3(y)}{(m)(q)} + 1\right] \text{ where } 2/3 \leqq (y)(m)(q) \leqq 1.0$$

or

$$K_X = 1/4\left[\frac{6(y)}{(m)(q)} - 1\right] \text{ where } 1/2 \leqq (31a) \leqq 2/3$$

For 120° phase belt winding

$$K_X = .75 \text{ when } 2/3 \leqq (y)/(m)(q)$$

or

$$K_X = .05\left[\frac{24(y)}{(m)(q)} -1\right] \text{ where } 1/2 \leqq \frac{(y)}{(m)(q)} \leqq 2/3$$

λ_i CONDUCTOR PERMEANCE

The specific permeance for the portion of the stator current that is embedded in the iron. This permeance depends upon the configuration of the slot (flux lines per ampere turn, per inch of stator stack).

(a) For open slots

$$\lambda_i = (C_X)\frac{20}{(m)(q)}\left[\frac{(h_2)}{(b_s)} + \frac{(h_1)}{3(b_s)} + \frac{(b_t)^2}{16(\tau_s)(g)} + \frac{.35(b_t)}{(\tau_s)}\right]$$

(b) For partially closed slots with constant slot width

$$\mathcal{T}_i = (C_X)\frac{20}{(m)(q)}\left[\frac{(h_o)}{(b_o)} + \frac{2(h_t)}{(b_o)+(b_s)} + \frac{(h_w)}{(b_s)} + \frac{(h_1)}{3(b_s)} + \frac{(b_t)^2}{16(\mathcal{T}_s)(g)} + \frac{.35bt}{\mathcal{T}_s}\right]$$

(c) For partially closed slots (tapered sides)

$$\mathcal{T}_i = (C_X)\frac{20}{(m)(q)}\left[\frac{(h_0)}{(b_0)} + \frac{2(h_t)}{(b_0)+(b_1)} + \frac{2(h_w)}{(b_1)+(b_2)} + \frac{(h_1)}{3(b_2)} + \frac{(b_t)^2}{16(\mathcal{T}_s)(g)} + \frac{.35bt}{\mathcal{T}_s}\right]$$

(d) For round slots

$$\mathcal{T}_i = (C_X)\frac{20}{(m)(q)}\left[.62 + \frac{(h_0)}{(b_0)}\right]$$

(e) For open slots with a winding of one conductor per slot

$$\mathcal{T}_i = (C_X)\frac{20}{(m)(q)}\left[\frac{(h_2)}{(b_s)} + \frac{(h_1)}{3(b_s)} + .6 + \frac{(g)}{2(\mathcal{T}_s)} + \frac{(\mathcal{T}_s)}{4(g)}\right]$$

K_E **LEAKAGE REACTIVE FACTOR** for end turn

$$K_E = \frac{\text{Calculated value }(L_E)}{\text{Value }(L_E)}$$

$\mathcal{T}_E$ **END WINDING PERMEANCE**

The specific permeance for the end extension portion of the stator winding.

$$\mathcal{T}_E = \frac{6.28(K_E)}{(l)(K_d)^2}\left[\frac{\phi_E L_E}{2n}\right]$$

WEIGHT OF STATOR COPPER in lbs.

$$\#\text{'s copper} = .321(n_s)(Q)(a_c)(\ell_t)$$

WEIGHT OF STATOR IRON in lbs.

$$\#\text{'s iron} = .283\ (b_{tm})(Q)(\ell_s)(h_s) + \pi(D) - (h_c)\ \ (h_c)(\ell_s)$$

K_s **CARTER COEFFICIENT**

For open slots

$$K_s = \frac{(\tau_s)\ 5(g) + (b_s)}{(\tau_s)\ 5(g) + (b_s) - (b_s)^2}$$

For partially closed slots

$$K_s = \frac{\tau_s\left[4.44(g) + .75(b_0)\right]}{\tau_s\left[4.44(g) + .75(b_0)\right] - (b_0)^2}$$

A_g **AIR GAP AREA**

The area of the gap surface at the stator bore.

$$\text{Gap Area} = \pi(d)(\ell)$$

g_e **EFFECTIVE AIR GAP** (in square inches)

$$g_e = (K_s)(g)$$

λ_a **AIR GAP PERMEANCE**

The specific permeance of the air gap.

$$\lambda_a = \frac{6.38(d)}{(P)(g_e)}$$

C_W **WINDING CONSTANT**

The ratio of the RMS line voltage for a full pitched winding to that which would be induced in all the phase conductors in series if the density were uniform and equal to the maximum value.

$$C_W = \frac{(E)(C_1)(K_d)}{\sqrt{2}\,(E_{PH})(m)}$$

Assuming $K_d = .955$, then $C_W = .225\ C_1$ for three phase delta machines

And $C_W = .390\ C_1$ for three phase star machines.

C_M **DEMAGNETIZING FACTOR** - direct axis.

$$C_M = \frac{(oc)\pi + \sin\left[(oc)\pi\right]}{4 \sin\ (oc)\ \pi/2}$$

C_q **CROSS MAGNETIZING FACTOR** - quadrature axis.

$$C_q = \frac{1/2 \cos\left[(oc)\ \pi/2\right] + (oc)\pi - \sin\left[(oc)\pi\right]}{4 \sin\left[(oc)\ \pi/2\right]}$$ valid for concentric poles

POLE DIMENSIONS LOCATIONS

Where:

b_h = width of pole head

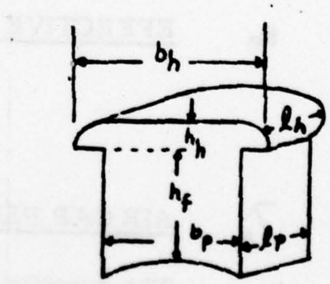
b_p = width of pole body

h_h = height of pole head at center

h_f = Height of pole body

ℓ_p = length of pole body

ℓ_h = length of pole head



all dimensions in inches

α **POLE EMBRACE**

$$\alpha = \frac{b_h}{p}$$

a_p **POLE AREA**

The effective cross sectional area of the pole.

$$a_p = (b_p)(\ell_p)(K_i) \quad \text{(square inches)}$$

$\mathcal{P}_{s\ell}$ **POLE SIDE LEAKAGE PERMEANCE**

$$\mathcal{P}_{s\ell} = \frac{(h_f)}{\pi/(P)\left[(d_r) - 2(h_h) - .5(h_f)\right] - (b_p)}$$

$\mathcal{P}_{t\ell}$ **POLE TIP LEAKAGE PERMEANCE**

$$\mathcal{P}_{t\ell} = \frac{2\left[(h_h) + (g) - (\tau_p)/18\right]}{(\tau_p) - (b_h)}$$

$\mathcal{P}_{e\ell}$ **POLE END LEAKAGE PERMEANCE**

$$\mathcal{P}_{e\ell} = \frac{2\left[(\ell_h) - (\ell)\right] + (h_f) + .25(b_p)}{(\ell)}$$

ϕ_T **TOTAL FLUX IN KILOLINES**

$$\phi_T = \frac{6(E)10^6}{(C_W)(n_e)(RPM)}$$

B_t **TOOTH DENSITY in Kilolines/in^2**

The flux density in the stator tooth at 1/3 of the distance from the minimum section.

$$B_t = \frac{\phi_T}{(Q)(\ell_s)(b_{t\,1/3})}$$

ϕ_P **FLUX PER POLE** in Kilolines

$$\phi_P = \frac{(\phi_T)(C_P)}{(P)}$$

B_c **CORE DENSITY** in Kilolines/in^2

The flux density in the stator core

$$B_c = \frac{(\phi_P)}{2(h_c)(\ell_s)}$$

B_g **GAP DENSITY** in Kilo Lines/in^2

The maximum flux density in the air gap

$$B_g = \frac{(\phi_T)}{\pi(d)(\ell)}$$

F_g **AIR GAP AMPERE TURNS**

The field ampere turns per pole required to force flux across the air gap when operating at no load with rated voltage.

$$F_g = \frac{(B_g)(g_e) \times 10^3}{3.19}$$

F_T **STATOR TOOTH AMPERE TURNS**

$$F_T = h_s \left[\text{NI/in at density } B_t\right]$$

F_c **STATOR CORE AMPERE TURNS**

$$F_c = \left[\frac{\pi[(D) - (h_c)]}{4(P)}\right] \left[\text{NI/in at density of } (B_c)\right]$$

F_s **STATOR AMPERE TURNS**, total

$$F_s = (F_T) + (F_c)$$

ϕ_ℓ **LEAKAGE FLUX** - at no load

$$\phi_\ell = .00638 \left[(\tau_{s\ell}) + (\tau_{e\ell}) + (\tau_{t\ell})\right]\left[(F_g) + (F_S)\right] (\ell_P)$$

ϕ_{PT} **TOTAL FLUX PER POLE** - at no load

$$\phi_{PT} = \phi_P + \phi$$

B_P **POLE DENSITY**

The flux density at the base of the pole.

$$B_P = \frac{(\phi_{PT})}{(a_P)}$$

F_P **POLE AMPERE TURNS** - at no load.

The ampere turns per pole required to force the flux through the pole and spider at no load rated voltage. In general the spider density is kept fairly low and its ampere turns can be neglected. The no load pole ampere turns per pole are calculated as the product of $\left[(h_f) + (h_h)\right]$ times the NI per inch at the density (B_P).

$$F_P = \left[(h_f) + (h_h)\right]\left[\text{NI/in at density } (B_P)\right]$$

F_{NL} **TOTAL AMPERE TURNS** - at no load.

The total ampere turns per pole required to produce rated voltage at no load.

$$F_{NL} = \left[(F_g) + (F_S) + (F_P)\right]$$

I_{FNL} **FIELD CURRENT** - at no load

$$I_{FNL} = (F_{NL})/(N_P)$$

E_F **FIELD VOLTS** - at no load.

This calculation is made with field resistance at 20°C for no load condition.

$$E_F = (I_{FNL})(R_{f\ cold})$$

S_F **CURRENT DENSITY** - at no load.

Amperes per square inch field conductor.

$$S_F = (I_{FNL})/(a_{cf})$$

A **AMPERE CONDUCTORS** per inch.

The effective ampere conductors per inch of stator periphery. This factor indicates the "specific loading" of the machine. It's value will increase with the rating and size of the machine and also will increase with the number of poles. It will decrease with increases in voltage or frequency. A is generally higher in single phase machines than in polyphase ones.

$$A = \frac{(I_{PH})(n_s)(K_P)}{(C)(\tau_s)}$$

X **REACTANCE FACTOR**

The reactance factor is the quantity by which the specific permeance must be multiplied to give percent reactance. Specific permeance is defined as the average flux per pole per inch of core length produced by unit ampere turns per pole.

$$X = \frac{100(A)(K_d)}{\sqrt{2}(C_1)(B_g) \times 10^3}$$

X_ℓ **LEAKAGE REACTANCE**

The leakage reactance of the stator for steady state conditions.

$$X_\ell = X\left[(\lambda_1) + (\lambda_E)\right]$$

In the case of two phase machines a component due to belt leakage must be included in the stator leakage reactance. This component is due to the harmonics caused by the concentration of the MMF into a small number of phase belts per pole and is negligible for three phase machines.

$$\tau_B = \frac{0.1(d)}{(P)(g_e)} \left[\frac{\sin \left[\frac{3(y)}{(m)(q)} \right] 90^\circ}{(K_P)} \right]$$

$$X_\ell = X \left[(\tau_i) + (\tau_E) + (\tau_B) \right] \text{ where } \tau_B = 0 \text{ for 3 phase machines.}$$

X_{ad} **REACTANCE - direct axis.**

This is the fictitious reactance due to armature reaction in the direct axis. (in percent)

$$X_{ad} = (X)(\tau_a)(C_1)(C_M)$$

X_{aq} **REACTANCE - quadrature axis.**

This is the fictitious reactance due to armature reaction in the quad axis. (in percent)

$$X_{aq} = (X)(C_q)(\tau_a)$$

$\rho_{D\,(hot)}$ **RESISTIVITY of damper bar at X_D °C**

$$\rho_{D(hot)} = (\rho_D) \left[\frac{(X_D\,^\circ C) + 234.5}{254.5} \right]$$

a_{cd} **CONDUCTOR AREA OF DAMPER BAR**

Calculate same as stator conductor area

$$a_{cd} = .25\pi (\text{damper bar dia})^2$$

or

$$a_{cd} = (h_{b1})\ (\text{damper bar width})$$

V_r **PERIPHERAL SPEED**

The velocity of the rotor surface in feet per minute.

$$V_r = \frac{\pi (d_r)(RPM)}{12}$$

X_d **SYNCHRONOUS REACTANCE** - direct axis.

The steady short circuit reactance in the direct axis. (percent)

$$X_d = (X_\ell) + (X_{ad}) = (130) + (131)$$

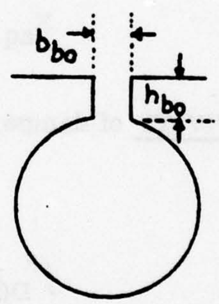
X_q **SYNCHRONOUS REACTANCE** - quadrature axis.

The steady state short circuit reactance in the quadrature.

$$X_q = (X_\ell) + (X_{aq}) = (130) + (132) \text{ (percent)}$$

DAMPER SLOT DIMENSIONS

b_{bo} - width of slot opening
h_{bo} - height of slot opening
h_b - diameter of round slot
h_{b1} - height of bar section of slot
b_{b1} - width of rectangular slot



All dimensions in inches

ρ_f (hot) **RESISTIVITY** of rotor field conductor at X_f°C

$$\rho_{f(hot)} = \rho_f \left[\frac{(X_f{}^\circ C) + 234.5}{254.5} \right]$$

R_f (cold) **COLD FIELD RESISTANCE** at 20°C

$$R_{f(cold)} = (\rho_f) \frac{(N_P)(P)(\ell_{tr}) \times 10^{-6}}{(a_{cf})}$$

R_f (hot) **HOT FIELD RESISTANCE** - Calculated at X_f°C

$$R_{f\ (hot)} = (\rho_{f\ hot}) \frac{(N_P)(P)(\ell_{tr}) \times 10^{-6}}{(a_{cf})}$$

WEIGHT OF ROTOR FIELD COPPER in lbs.

The answer is given in lbs. based on the density of copper. If any other material is used, the answer on the output sheet can be converted by the designer by multiplying by the ratio of densities.

$$\#\text{'s of copper} = .321(N_P)(P)(\ell_{tr})(a_{cf})$$

$\mathcal{T}_b$ **PERMEANCE OF DAMPER BAR**

The permeance of that portion of the damper bar that is embedded in pole iron.

For round slot

$$\mathcal{T}_b = 6.38 \left[\frac{(h_{bo})}{(b_{bo})} + .62 + .5\right]$$

For rectangular slot

$$\mathcal{T}_b = 6.38 \left[\frac{(h_{bo})}{(b_{bo})} + \frac{(h_{b1})}{3(b_{b1})} + .5\right]$$

$\mathcal{T}_{pt}$ **PERMEANCE OF END PORTION OF DAMPER BARS**

$$\mathcal{T}_{pt} = 6.38 \left\{\frac{(b_h) - (\mathcal{T}_b)\left[(n_b) - 1\right]}{3(g_e)}\right\}$$

X_F **FIELD LEAKAGE REACTANCE** in percent

$$X_F = (X_{ad})\ 1 - \left[\frac{(C_1)/(C_m)}{2(C_P) + \frac{4(\mathcal{T}F)}{(\mathcal{T}_a)}}\right]$$

L_f **FIELD SELF INDUCTANCE**, henries

$$L_f = (N_P)^2(P)(\ell_P)\left[(C_P)(\lambda_a)\frac{\pi}{2} + (\lambda_f)\right] \times 10^{-8}$$

λ_F **ROTOR LEAKAGE PERMEANCE**

$$\lambda_F = 4.25\left[(\lambda_{s\ell}) + 1.5(\lambda_{t\ell})\right] + 6.38(\lambda_{e\ell})$$

λ_{Dd} **PERMEANCE OF DAMPER BAR** - in direct axis.

$$\lambda_{Dd} = \left\{\cos\left[\frac{\{(n_b) - 1\}\quad(\tau_b)\pi}{2(\tau_P)}\right]\right\}\left\{\frac{\{(\lambda_b) + (\lambda_{Pt})\}\quad(\lambda_F)}{(\lambda_b + \lambda_{Pt} + \lambda_F)}\right\}$$

X_{Dd} **DAMPER LEAKAGE REACTANCE** - in direct axis (percent)

$$X_{Dd} = X\lambda_{Dd}$$

λ_{Dq} **PERMEANCE IN QUADRATURE AXIS**

For round slot

$$\lambda_{D_q} = \frac{20(\tau_b)}{(\tau_P)}\left[\frac{(h_{bo})}{(b_{bo})} + .62 + .5 + \frac{(g)}{(\tau_b)}\right]$$

For rectangular slot

$$\lambda_{(Dq)} = \frac{20(\tau_b)}{(\tau_P)}\left[\frac{(h_{bo})}{(b_{bo})} + \frac{(h_{b1})}{3(b_{b1})} + .5 + \frac{(g)}{(\tau_b)}\right]$$

X_{Dq} **DAMPER LEAKAGE REACTANCE** - in quadrature axis (percent)

$$X_{Dq} = X(\lambda_{Dq})$$

X'_{du} **UNSATURATED TRANSIENT REACTANCE** (percent)

$$X'_{du} = (X\ ) + (X_f)$$

X'_d **SATURATED TRANSIENT REACTANCE** (percent)

$$X'_d = .88(X'_{du})$$

X''_d **SUBTRANSIENT REACTANCE** in direct axis (percent)

When damper bars exist

$$X''_d = (X\ ) + (X_{Dd})$$

When no damper bars exist

$$X''_d = (X'_d)$$

X''_q **SUBTRANSIENT REACTANCE** in quadrature axis (percent)

When damper bar exists

$$X''_q = (X\ ) + (X_{Dq})$$

When no damper bars exist

$$X''_q = X_q$$

X_2 **NEGATIVE SEQUENCE REACTANCE**

The reactance due to field which rotates at synchronous speed in a direction opposite to that of the rotor. (percent)

$$X_2 = .5\ X''_d + X''_q$$

X_0 **ZERO SEQUENCE REACTANCE**

The reactance drop across any one phase (star connected) for unit current in each of the phases. The machine must be star connected for otherwise no zero sequence current can flow and the term then has no significance. (in percent)

$$X_o = X \left\{ \frac{(K_{xo})}{(K_{x1})} \left[(\tau_i) + (\tau_{Bo}) \right] + \frac{1.667 \ (h_1) + 2(h_3)}{(m)(q)(K_p)^2(K_d)^2(b_s)} + .2(\tau_E) \right\}$$

K_{xo}

$$K_{xo} = \frac{3(\gamma)}{(m)(q)} - 2$$

K_{x1}

$$K_{x1} = \left[\frac{3(\gamma)}{4(m)(q)} + \frac{1}{4} \right]$$

or

$$K_{x1} = \left[\frac{3(\gamma)}{4(m)(q)} - \frac{1}{4} \right]$$

τ_{Bo}

$$\tau_{Bo} = \frac{(K_{xo})}{(K_p)^2} \left[.07(\tau_a) \right]$$

or

$$\tau_{Bo} = \frac{\frac{(K_{xo})}{(K_{x1})} (\tau_{Dq}) + \frac{(K_{xo})}{(K_p)^2} \left[.07(\tau_a) \right]}{\left\{ \frac{(K_{xo})}{(K_{x1})} (\tau_{Dq}) \right\} \left\{ \frac{(K_{xo})}{(K_p)^2} \left[.07(\tau_a) \right] \right\}}$$

T'_{do} **OPEN CIRCUIT TIME CONSTANT**

The time constant of the field winding with the stator open circuited and with negligible external resistance and inductance in the field circuit. Field resistance at room temperature (20°C) is used in this calculation. (seconds)

$$T'_{do} = \frac{L_F}{R_F}$$

See appendix for explanation of time constants.

T_a **ARMATURE TIME CONSTANT**

Time constant of the D. C. component. In this calculation stator resistance at room temperature (20°C) is used. (seconds)

$$T_a = \frac{X_2}{200\pi(f)(r_a)}$$

where

$$r_a = \frac{(m)(I_{PH})^2(R_{SPHcold})}{(\text{Rated KVA}) \times 10^3}$$

T_d' **TRANSIENT TIME CONSTANT**

The time constant of the transient reactance component of the alternating wave. (seconds)

$$T_d' = \frac{(X_d')}{(X_d)}(T_{do}')$$

T_d'' **SUBTRANSIENT TIME CONSTANT**

The time constant of the subtransient component of the alternating wave. This value has been determined empirically from tests on large machines. Use following values.

$$T_d'' = .035 \text{ second at 60 cycle}$$

$$T_d'' = .005 \text{ second at 400 cycle}$$

F_{SC} **SHORT CIRCUIT AMPERE TURNS**

The field ampere turns required to circulate rated stator current when the stator is short circuited.

$$F_{SC} = (X_d)(F_g)$$

SCR **SHORT CIRCUIT RATIO**

The ratio of the field current to produce rated voltage on open circuit to the field current required to produce rated current on short circuit.

Since the voltage regulation depends on the leakage reactance and the armature reaction, it is closely related to the current which the machine produces under short circuit conditions, and therefore is directly related to the SCR.

$$SCR = \frac{F_{NL}}{F_{SC}}$$

I^2R_R **ROTOR I^2R** - at no load.

The copper loss in the field winding is calculated with cold field resistance at 20°C no load condition. (watts)

$$\text{Rotor } I^2R = (I_{FNL})^2 (R_{fcold})$$

F&W **FRICTION & WINDAGE LOSS** (Watts)

$$F\&W = 2.52 \times 10^{-6} (d_r)^{2.5} (\ell_b)(RPM)^{1.5}$$

For gases or fluids other than standard air, the fluid density and viscosity must be considered. The formula given in the manual can be modified by the factors.

$$\left(\frac{\rho}{.0765}\right)^{.8} \left(\frac{u}{.0435}\right)^{.2}$$

where

ρ - density - Lbs FT^{-3}
μ - viscosity LBS FT^{-1} HR^{-1}
.0765 - density std. air
.0435 - viscosity std. air

W_{TNL} **STATOR TEETH LOSS** - at no load.

The no load loss (W_{TNL}) consists of eddy current and hysteresis losses in the iron. For a given frequency the no load tooth loss will vary as the square of the flux density. (watts)

$$W_{TNL} = .453(b_{t\,1/3})(Q)(\ell_s)(h_s)(K_Q)$$

where

$$K_Q = (k) \left[\frac{(B_t)}{(B)}\right]^2$$

W_c **STATOR CORE LOSS**

The stator core losses are due to eddy currents and hysteresis and do not change under load conditions. For a given frequency the core loss will vary as the square of the flux density (B_c). (watts)

$$W_c = 1.42 \left[(D) - (h_c)\right] (h_c)(\ell_s)(K_Q)$$

where

$$K_Q = (k)\left[\frac{(B_c)}{(B)}\right]^2$$

W_{PNL} **POLE FACE LOSS** - at no load.

$$W_{PNL} = \pi(d)(\ell)(K_1)(K_2)(K_3)(K_4)(K_5)(K_6)$$

K_1 K_1 is derived empirically and depends on lamination material and thickness.

K_1 = 1.17 for .028 lam thickness, low carbon steel
= 1.75 for .063 lam thickness, low carbon steel
= 3.5 for .125 lam thickness, low carbon steel
= 7.0 for solid core

K_2

$$K_2 = fn(B_G) = 6.1 \times 10^{-5} (B_G)^{2.5}$$

K_3

$$K_3 = fn(F_{SLT}) = 1.5147 \times 10^{-5} (F_{SLT})^{1.65}$$

where

$$F_{SLT} = \frac{(RPM)}{60} (Q)$$

K_4

For $\tau_s \leqq .9$

$$K_4 = fn(\tau_s) = .81(\tau_s)^{1.285}$$

For $.9 \leqq \tau_s \leqq 2.0$

$$K_4 = fn(\tau_s) = .79(\tau_s)^{1.145}$$

For $\tau_s > 2.0$

$$K_4 - fn(\tau_s) = .92(\tau_s)^{.79}$$

K_5 K_5 can be calculated as follows:

For $(b_s)/(g) \leqq 1.7$

$$K_5 = fn(b_s/g) = .3\left[(b_s)/(g)\right]^{2.31}$$

NOTE: For partially open slots substitute b_o for b_s in equations shown.

For $1.7 < (b_s)/(g) \leqq 3$

$$K_5 = fn(b_s)/(g) = .35\left[(b_s)/(g)\right]^2$$

For $3 < (b_s)/(g) \leqq 5$

$$K_5 = fn(b_s)/(g) = .625\left[(b_s)/(g)\right]^{1.4}$$

For $(b_s)/(g) > 5$

$$K_5 = fn\left[(b_s)\right]/(g) = 1.38\left[(b_s)/(g)\right]^{.965}$$

K_6 K_6 can be calculated as follows:

$$K_6 = fn(C_1) = 10^{\left[.9323(C_1) - 1.60596\right]}$$

$$= 10^{\left[.9323(71) - 1.60596\right]}$$

W_{DNL} DAMPER LOSS - at no load at 20°C.

This loss is produced slot ripple in the damper winding.

$$W_{DNL} = \frac{1.246(P)(n_b)(\ell_b)(\rho_D)}{(a_{cd}) \times 10^3} (\tau_s)(B_g)(K_{P1})(K_g)^2$$

$$\left\{ (K_{f1})\left[\frac{K_{W1}}{2(\tau_s) + \left[(\tau_g)/(K_{\phi 1})\right]}\right]^2 + (K_{f2})\left[\frac{(K_{W2})}{2(\tau_s) + \left[(\tau_g)/(K_{\phi 2})\right]}\right]^2 \right\}$$

Where

$$K_{P1} = 1 - \frac{1}{\sqrt{1 + \left[(b_s)/2(g)\right]^2}}$$

Where

$$K_g = (K_s)$$

Where

$$g' = (K_g)(g)$$

$$S_1 = .32\sqrt{\frac{(f_{S1})}{(\rho_D)}}\ (h_b)$$

$$S_2 = .32\sqrt{\frac{(f_{S2})}{(\rho_D)}}\ (h_b)$$

Where

$$f_{S1} = 2qmf$$

$$f_{S2} = 2(f_{S1})$$

$$\tau_C = \frac{.75}{(K_{f1})} = \frac{.75}{(193)}$$ For round or square slots

or

$$\tau_C = \frac{(h_{b1})}{3(b_{b1})(K_{f1})}$$

Where

$$\tau_S = \frac{(h_{bo})}{(b_{bo})} + (\tau_t) + (\tau_C)$$

Where

$$\tau_g = \frac{(\tau b)}{(g')}$$

<u>TOTAL LOSSES</u> - at no load.

Sum of all losses. (in watts)

Total losses = (Rotor I^2R) + (F & W) + (Stator Teeth Loss) + (Stator Core Loss) + (Pole Face Loss) + (Damper Loss)

$\phi_{\ell\ell}$ **LEAKAGE FLUX PER POLE** at 100% load

$$\phi_{\ell\ell} = \phi_{\ell}\left\{\frac{(e_d)(F_g) + \left[1 + \cos(\theta)\right](F_T) + (F_C)}{(F_g) + (F_T) + (F_C)}\right\}$$

Where

$$e_d = \cos \epsilon + \frac{(X_d)}{100} \sin \Psi$$

Where

$$\theta = \cos^{-1}\left[(\text{Power Factor})\right]$$

Where

$$\Psi = \tan^{-1}\left[\frac{\sin(\theta) + (X_q)/(100)}{\cos(\theta)}\right]$$

Where

$$\epsilon = \Psi - \theta$$

ϕ_{PL} **FLUX PER POLE** at 100% load, Kilolines

For P.F. 0 to .95

$$\phi_{PL} = (\phi_P)\left[(e_d) - \frac{.93(X_{ad})}{100} \sin(\Psi)\right]$$

For P.F. .95 to 1.0

$$\phi_{PL} = (\phi_P)(K_c)$$

ϕ_{PTL} **TOTAL FLUX PER POLE** at 100% load, Kilolines

$$\phi_{PTL} = \phi_{PL} + \phi_{\ell\ell}$$

B_{PL} **FLUX DENSITY AT BASE OF POLE** at 100% load, Kl/in

$$B_{PL} = \frac{\phi_{PTL}}{a_P}$$

F_{PL} **AMPERE TURNS PER POLE** at 100% load

$$F_{PL} = \left[(h_f) + (h_h)\right] \left[\text{NI/in at density } (B_{PL})\right]$$

F_{FL} **TOTAL AMPERE TURNS PER POLE** at 100% load

The ampere turns per pole required to produce rated load.

$$F_{FL} = (e_d)(F_g) + \left[1 + \cos(\theta)\right] (F_T) + (F_C) + (F_{PL})$$

I_{FFL} **FIELD CURRENT** at 100% load, amperes

$$I_{FFL} = (F_{FL})/(N_P)$$

E_{FFL} **FIELD VOLTS** at 100% load

This calculation is made with hot field resistance at expected temperature at 100% load.

$$\text{Field Volts} = (I_{FFL})(R_{f\,hot})$$

S_{FL} **CURRENT DENSITY** at 100% load amperes per square inch

$$\text{Current Density} = (I_{FFL})/(a_{cf})$$

I^2R_R **ROTOR I^2R at 100% load**

The copper loss in the field winding is calculated with hot field resistance at expected temperature for 100% load condition. (watts)

$$\text{Rotor } I^2R = (I_{FFL})^2(R_{f\,hot})$$

W_{TFL} **STATOR TEETH LOSS** at 100% load

The stator tooth loss under load increases over that of no load because of the parasitic fluxes caused by the ripple due to the rotor damper bar slot openings. (watts)

$$W_{TFL} = \left\{2\left[.27\ \frac{(X_d)}{100}\quad\frac{(\%\ \text{Load})}{100}\right]^{1.8} + 1\right\}(W_{TNL})$$

W_{PFL} POLE FACE LOSS at 100% load (watts)

$$W_{PFL} = \left\{ \left[\frac{(K_{sc})(I_{PH}) \frac{(\%\ Load)}{100} (n_s)}{(C)(F_g)} \right]^2 + 1 \right\} (W_{PNL})$$

W_{DFL} DAMPER LOSS at 100% load (watts)

$$W_{DFL} = \left\{ \left[\frac{(K_{sc})(I_{PH}) \frac{(\%\ Load)}{100} (n_s)}{(C)(F_g)} \right]^2 + 1 \right\} (W_{DNL})$$

I^2R_L STATOR I^2R at 100% load

The copper loss based on the resistance of the winding. Calculate at the max expected operating temperature. (watts)

$$I^2R_L = (m)(I_{PH})^2 \ (R_{SPH\ hot}) \ \frac{(\%\ Load)}{100}$$

EDDY LOSS - Stator I^2R loss due to skin effect (watts)

$$\text{Eddy Loss} = \left[\frac{(EF_{top}) + (EF_{bot})}{2} - 1 \right] (\text{Stator } I^2R)$$

TOTAL LOSSES at 100% load - sum of all losses at 100% load.

$$\text{Total Losses} = (\text{Rotor } I^2R) + (F \,\&\, W) + \text{Stator Teeth Loss}) + (\text{Stator Core Loss}) + (\text{Pole Face Loss}) + (\text{Damper Loss}) + (\text{Stator } I^2R) + \text{Eddy})$$

RATING IN KILOWATTS at 100% load

$$\text{Rating} = 3(E_{PH})(I_{PH}) \ (P.F.) \ \frac{(\%\ Load)}{100}$$

% LOSSES = $\left[\Sigma\text{Losses}/(\text{Rating} + \Sigma\text{Losses}) \right] 100$

% EFFICIENCY = 100% - % Losses

IX. LIST OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

List of Symbols

Symbol	Definition
KVA	GENERATOR KVA
E	LINE VOLTS
E_{PH}	PHASE VOLTS
m	PHASES
f	FREQUENCY
P	POLES
RPM	SPEED
I_{PH}	PHASE CURRENT
P.F.	POWER FACTOR
K_c	ADJUSTMENT FACTOR
B	DENSITY
d	STATOR PUNCHING I.D.
D	STATOR PUNCHING O.D.
ℓ	GROSS STATOR CORE LENGTH
n_v	NUMBER OF DUCTS
b_v	RADIAL DUCT WIDTH
K_I	STACKING FACTOR (STATOR)
k	WATTS/LB
b_o	SLOT OPENING
b_1	SLOT WIDTH ACROSS TOP
b_s	SLOT WIDTH ACROSS BOTTOM
h_s	SLOT DEPTH
Q	STATOR SLOTS

LIST OF SYMBOLS - CONTINUED

Symbol	Definition
n_s	CONDUCTORS/SLOT
y	SLOTS SPANNED
c	PARALLEL CIRCUITS
N_{ST}	NUMBER OF STRANDS PER CONDUCTOR IN DEPTH
N'_{ST}	NUMBER OF STRANDS PER CONDUCTOR
d_b	DIAMETER OF BENDER PIN
e^2	COIL EXTENSION BEYOND CORE
h_{ST}	HEIGHT OF UNINSULATED STRAND
h'_{ST}	DISTANCE BETWEEN CENTERLINES OF STRANDS IN DEPTH
τ_{SK}	SKEW
$X_s{}^\circ C$	STATOR TEMP °C
ρ_s	RESISTIVITY OF STATOR WINDING
ρ_S (hot)	RESISTIVITY OF STATOR WINDING
g_{min}	MINIMUM AIR GAP
g_{max}	MAXIMUM AIR GAP
C_1	THE RATIO OF MAXIMUM FUNDAMENTAL of the field form to the actual maximum of the field form.
C_W	WINDING CONSTANT
C_P	POLE CONSTANT - The ratio of the average to the maximum value of the field form.
ϕ_T	TOTAL FLUX IN KILOLINES
L_E	END EXTENSION LENGTH
C_m	DEMAGNETIZING FACTOR, RATIO OF FIELD-POLE AMPERE-TURNS TO EQUIVALENT PEAK SINE-WAVE ARMATURE AMPERE-TURNS
C_q	CROSS MAGNETIZING FACTOR

LIST OF SYMBOLS - CONTINUED

Symbol	Definition
b_h	POLE HEAD WIDTH
b_p	POLE BODY WIDTH
h_h	POLE HEAD HEIGHT
h_f	POLE BODY HEIGHT
ℓ_p	POLE BODY LENGTH
ℓ_n	POLE HEAD LENGTH
oC	POLE EMBRACE
d_r	ROTOR O.D.
K_1	STACKING FACTOR (ROTOR)
X_1	POLE FACE LOSS FACTOR
b_{bo}	WIDTH OF SLOT OPENING
h_{bo}	HEIGHT OF SLOT OPENING
h_{b1}	RECTANGULAR BAR THICKNESS
b_{bL}	RECTANGULAR SLOT WIDTH
n_b	NUMBER OF DAMPER BARS
ℓ_b	DAMPER BAR LENGTH
τ_b	DAMPER BAR PITCH
ρ_b	DAMPER BAR RESISTIVITY @ 20°C
$X_D{}^\circ C$	DAMPER BAR TEMP °C
N_p	NO. OF FIELD TURNS
ℓ_{tr}	MEAN LENGTH FIELD TURN
$X_{f^\circ C}$	FIELD TEMP IN °C
ρ_f	RESISTIVITY OF ROTOR WINDING AT 20°C COLD
ρ_f	RESISTIVITY OF ROTOR WINDING AT $X_{f^\circ C}$

LIST OF SYMBOLS - CONTINUED

Symbol	Definition
F & W	FRICTION & WINDAGE LOSS
ℓ_s	SOLID CORE LENGTH
h_c	DEPTH BELOW SLOTS
τ_s	STATOR SLOT PITCH
$\tau_{s\ 1/3}$	STATOR SLOT PITCH
K_{SK}	SKEW FACTOR
K_d	DISTRIBUTION FACTOR
K_p	PITCH FACTOR
n_e	TOTAL EFFECTIVE CONDUCTORS
a_c	CONDUCTOR AREA OF STATOR WINDING
S_S	CURRENT DENSITY
ℓ_t	1/2 MEAN TURN
R_{SPH}	COLD STATOR RESISTANCE/PHASE
R_{SPH}	HOT STATOR RESISTANCE/PHASE
EF (top)	EDDY FACTOR TOP
EF (bot)	EDDY FACTOR BOTTOM
b_{tm}	STATOR TOOTH WIDTH
$b_{t\ 1/3}$	STATOR TOOTH WIDTH
b_t	TOOTH WIDTH AT STATOR I.D. IN INCHES
g	MAIN AIR GAP IN INCHES
C_X	REDUCTION FACTOR used in calculating (62)
λ_i	SLOT LEAKAGE PERMEANCE
K_E	LEAKAGE REACTIVE FACTOR
λ_E	END WINDING FLUX LEAKAGE PERMEANCE

LIST OF SYMBOLS - CONTINUED

Symbol	Definition
q	SLOTS PER POLE PER PHASE
n_s	CONDUCTORS PER SLOT
τ_p	POLE PITCH
a_p	POLE AREA
τ_e	POLE END LEAKAGE PERMEANCE
τ_t	POLE TIP LEAKAGE PERMEANCE
$\tau_{s\ell}$	POLE SIDE LEAKAGE PERMEANCE
a_{cf}	AREA OF CONDUCTOR - The actual area of the conductor taking into account the corner radius.
R_f (cold)	COLD FIELD RESISTANCE @ 20°C
R_f (hot)	HOT FIELD RESISTANCE AT X°C
V_r	PERIPHERAL SPEED OF ROTOR
ℓ_{tr}	MEAN TURN - The mean length of rotor turn. This value must be calculated from a layout of the rotor winding.
T'_{do}	OPEN CIRCUIT TIME CONSTANT
T_a	ARMATURE TIME CONSTANT
T''_d	SUBTRANSIENT TIME CONSTANT
F_{sc}	SHORT CIRCUIT AMPERE TURNS
S_{CR}	SHORT CIRCUIT RATIO
K_s	CARTER COEFFICIENT
A_g	MAIN AIR GAP AREA
λ_a	AIR GAP PERMEANCE
g_e	EFFECTIVE GAP - The effective single air gap.

$g_e = K_s K_r g$ (for rotors with slotted pole centers) = (67) (308) (59)

$g_e = K_s g$ (for rotors with solid pole centers) = (67) (59)

LIST OF SYMBOLS - CONTINUED

Symbol	Definition
A	AMPERE CONDUCTORS PER INCH
X	REACTANCE FACTOR
X_ℓ	LEAKAGE REACTANCE
X_{ad}	REACTANCE DIRECT AXIS REACTANCE OF ARMATURE REACTION
X_{aq}	QUADRATURE REACTANCE
X_d	SYNCHRONOUS REACTANCE $X_d = X + X_{ad} = (130) + (131)$
X_q	PER UNIT QUADRATURE-AXIS SYNCHRONOUS REACTANCE
X_f	FIELD LEAKAGE REACTANCE
L_f	FIELD SELF INDUCTANCE
$X_{D\phi}$	DAMPER LEAKAGE REACTANCE DIRECT
$X_{D\delta}$	DAMPER LEAKAGE REACTANCE QUADRATURE
B_g	GAP DENSITY IN KILOLINES/in^2
B_c	CORE DENSITY IN KILOLINES/in^2
F_T	STATOR TOOTH AMPERE TURNS
F_c	STATOR CORE AMPERE-TURNS
F_s	STATOR AMPERE TURNS
I_F	FIELD CURRENT
E_F	FIELD VOLTS
S_F	CURRENT DENSITY AMPS/IN^2 IN FIELD CONDUCTOR
F_g	AIR-GAP AMPERE-TURNS
ϕ_ℓ	LEAK FLUX
ϕ_P	FLUX PER POLE IN KILOLINES
B_t	TOOTH DENSITY IN KILOLINES/in^2
F_p	POLE AMP TURNS
$F_{f\ell}$	TOTAL AMP TURNS

LIST OF SYMBOLS - CONTINUED

Symbol	Definition
F_{ff}	FIELD AMPS
S	CURRENT DENSITY IN FIELD CONDUCTORS
E_F	FIELD VOLTS
I^2R_R	ROTOR I^2R
W_T	STATOR TEETH LOSS
W_c	STATOR CORE LOSS
W_P	POLE FACE LOSS
W_D	DAMPER LOSS
I^2R	STATOR I^2R
a	RATIO OF POLE ARC TO POLE PITCH
ϕ	POWER FACTOR ANGLE OF THE LOAD
ϕ	ANGLE IN ELECTRICAL RADIANS, MEASURED FROM CENTER-LINE OF POLE TOWARDS CENTERLINE BETWEEN POLES
T_r	POLE PITCH MEASURED AT STATOR BORE
d	A CONSTANT FOR LOCATING POINT III ON THE AUXILIARY T PLANE OF THE SCHWARZ-CHRISTOFFEL TRANSFORMATION
b	DISTANCE ALONG STATOR BORE BETWEEN END OF POLE EMBRACE AND ADJACENT CENTER-LINE BETWEEN POLES
C_n	nth HARMONIC OF THE FIELD FORM, THE RATIO OF THE MAXIMUM nth HARMONIC TO THE ACTUAL MAXIMUM VALUE OF THE FIELD FORM (FIGURED WITH DIRECT-CURRENT FIELD EXCITATION ACTING ALONE AND WITH NO SATURATION)
C_{na}	RATIO OF THE PEAK nth HARMONIC OF THE FIELD FORM PRODUCED BY UNIT PEAK FUNDAMENTAL ARMATURE MAGNETOMOTIVE FORCE, TO THE MAXIMUM ACTUAL VALUE OF THE FIELD FORM PRODUCED BY UNIT MAGNETOMOTIVE FORCE FROM THE FIELD POLES (FIGURED WITH NO SATURATION)
C_{nad}	RATIO OF THE PEAK nth HARMONIC OF THE FIELD FORM PRODUCED BY UNIT PEAK FUNDAMENTAL ARMATURE MAGNETOMOTIVE FORCE IN THE DIRECT AXIS, TO THE MAXIMUM ACTUAL VALUE OF THE FIELD FORM PRODUCED BY UNIT MAGNETOMOTIVE FORCE FROM THE FIELD POLES (FIGURED WITH NO SATURATION)

LIST OF SYMBOLS - CONTINUED

Symbol	Definition
C_{nat}	INTERPOLAR COMPONENT OF C_{nad}
C_{nadv}	INTRAPOLAR COMPONENT OF C_{nad}
C_{naq}	RATIO OF THE PEAK nth HARMONIC OF THE FIELD FORM PRODUCED BY UNIT PEAK FUNDAMENTAL ARMATURE MAGNETOMOTIVE FORCE IN THE QUADRATURE AXIS, TO THE MAXIMUM ACTUAL VALUE OF THE FIELD FORM PRODUCED BY UNIT MAGNETOMOTIVE FORCE FROM THE FIELD POLES (FIGURED WITH NO SATURATION)
C_{naqt}	INTERPOLAR COMPONENT OF C_{naq}
C_{naqp}	INTRAPOLAR COMPONENT OF C_{naq}
C_{nt}	INTERPOLAR COMPONENT OF C_n
C_{np}	INTRAPOLAR COMPONENT OF C_n
C_r	FUNDAMENTAL OF THE FIELD FORM, THE RATIO OF THE MAXIMUM FUNDAMENTAL TO THE ACTUAL MAXIMUM VALUE OF THE FIELD FORM (FIGURED WITH DIRECT-CURRENT FIELD EXCITATION ACTING ALONE AND WITH NO SATURATION)
F	PEAK FUNDAMENTAL ARMATURE AMPERE-TURNS
F_d	PEAK FUNDAMENTAL ARMATURE AMPERE-TURNS IN THE DIRECT AXIS
F_g	NO-LOAD AIR-GAP AMPERE-TURNS
F_L	D-C FIELD AMPERE-TURNS UNDER LOAD
F_q	PEAK FUNDAMENTAL ARMATURE AMPERE-TURNS IN THE QUADRATURE AXIS
g_n	SINGLE AIR GAP AT CENTER OF POLE FACE
g_x	SINGLE AIR GAP AT POLE TIP
H_n	PER UNIT CONTENT OF THE nth HARMONIC IN A SINGLE, UNSKEWED ARMATURE CONDUCTOR
I	PER UNIT LOAD CURRENT
I_d	PER UNIT LOAD CURRENT IN THE DIRECT AXIS
I_q	PER UNIT LOAD CURRENT IN THE QUADRATURE AXIS
n	ORDER OF HARMONIC

LIST OF SYMBOLS - CONTINUED

Symbol	Definition
P	NUMBER OF POLES
R_L	PER UNIT LOAD RESISTANCE
u	MAGNETIC FLUX, USED AS ABSCISSA OF THE COMPLEX W PLANE
V	PER UNIT TERMINAL VOLTAGE
v	MAGNETIC POTENTIAL, USED AS ORDINATE OF THE COMPLEX W PLANE
w	FIELD FUNCTION, COMPLEX VARIABLE WITH REAL PART u AND IMAGINARY PART v
X_L	PER UNIT LOAD REACTANCE
x	ABSCISSA OF THE COMPLEX Z PLANE
X_d''	PER UNIT DIRECT-AXIS SUBTRANSIENT REACTANCE
y	ORDINATE OF THE COMPLEX Z PLANE
Z_{Gn}	PER UNIT INTERNAL GENERATOR IMPEDANCE TO nth HARMONIC CURRENT
Z_L	PER UNIT LOAD IMPEDANCE
Z_{Ln}	PER UNIT LOAD IMPEDANCE TO nth HARMONIC CURRENT
z	COMPLEX VARIABLE WITH REAL PART x AND IMAGINARY PART y
C	PARALLEL PATHS
r	ABSCISSA OF THE T PLANE OF THE SCHWARZ-CHRISTOFFEL TRANSFORMATION
s	ORDINATE OF THE T PLANE OF THE SCHWARZ-CHRISTOFFEL TRANSFORMATION
t	COMPLEX VARIABLE, WITH REAL PART 4 AND IMAGINARY PART s
U	MAGNETIC POTENTIAL OF THE POLE FACE

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